PROJECT GALILEO AT JUPITER

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Abstract

Galileo made a highly successful arrival at Jupiter on December 7, 1995. The Galileo Atmospheric Entry Probe transmitted the first ever direct measurements of an outer planet to the Orbiter mothership for nearly one hour while descending to a pressure depth of 23 bar- far beyond the 10 bar mission requirement. After storing the Probe data onboard, the Orbiter performed an essentially perfect insertion burn to become the first spacecraft to orbit an outer planet. In mid March 1996, the third and final burn of Galileo's 400N main engine will raise the prijove distance so that the Orbiter can survive the radiation dose accumulation for the subsequent eleven orbits. The new flight software providing the onboard editing, compression, and telemetry capabilities required to perform the Orbiter mission via the low-gain antenna will be uplinked in May preparatory to the first satellite encounter Ganymede 1 on June 27. The second satellite encounter Ganymede 2 occurs on September 6.

This paper will summarize: 1) the Probe mission results both engineering and scientific, 2) the problems with the Orbiter tape recorder and its recovery, 3) the Orbiter engineering operations including the loading and performance of the new flight software, and 4) early science results from the arrival and first two orbits and Ganymede encounters. Overall, mission status and the forecast for the remainder of the Orbiter's two year primary mission will also be provided.

Introduction

Galileo's arrival at Jupiter on December 7th was a tremendous success. Eighteen years of dogged tenacity and imaginative engineering solutions to some of the toughest technical and political problems ever faced by a project have finally paid off. Galileo's success is truly a triumph of the human spirit and creativity.

Entering the Jupiter atmosphere is by far the most difficult planetary entry in our solar system. Galileo did it flawlessly. As reported last year[1], the Orbiter released the Probe on 13 July 1995 for its five month, solo, unguided ballistic flight to the Jupiter entry corridor. The Orbiter aimed the Probe so accurately that the Probe used only about 15% of its entry corridor margin. The heat shield protected the descent module from outside entry temperatures that reached 25,000 F at the stagnation point in front of the Probe and all elements of the Probe withstood nearly 230g entry structural load. All seven of the Probe's scientific instruments worked. The primary requirement was to reach a pressure depth of 10 bars- the Probe transmitted data to the Orbiter continuously for 57.6 minutes reaching a depth of 23 bars! The Relay Link began at four minutes after entry, so transmission ended 61.4 minutes after entry. The original mission design ended the Relay at 60 minutes after entry- the Orbiter propellant savings achieved by the VEEGA trajectory allowed the Orbiter support of the Link to 78 minutes after entry to ensure getting every bit (*literally*) of data the Probe might transmit. The Probe descent mission actually started about a minute late due apparently to a wiring problem with the g-switches that told the Probe when to deploy the parachute. The Probe stopped transmitting when the transmitters got too hot. The descent module's inside temperatures were much closer to the outside temperature during *descent* than expected.

The Orbiter returned essentially all of the Probe data, both from the abbreviated direct computer memory storage[1] and from the Tape Recorder. The return was completed 15 April 1996. This was one month later than previously planned in order to provide for interim tape recorder diagnostics.

Reference 1 described the plan to take a color image of Jupiter two months before arrival- this would be the only image returned before the new software[1] was onboard. Immediately after taking this image, the Tape Recorder would not rewind. Telemetry data showed that the Recorder was running but the tape wasn't moving. Every imaginable explanation was that the Recorder was broken and unrecoverable. The Tape Recorder was the primary means for getting the Probe data; without it only the abbreviated data set to be stored in the Orbiter computer memory would be available. And, the Orbiter mission without the High Gain Antenna was crucially dependent on the Recorder- there would be no images without the Recorder!

So two months before arrival, the Project urgently jumped into three new efforts: troubleshoot the Recorder,

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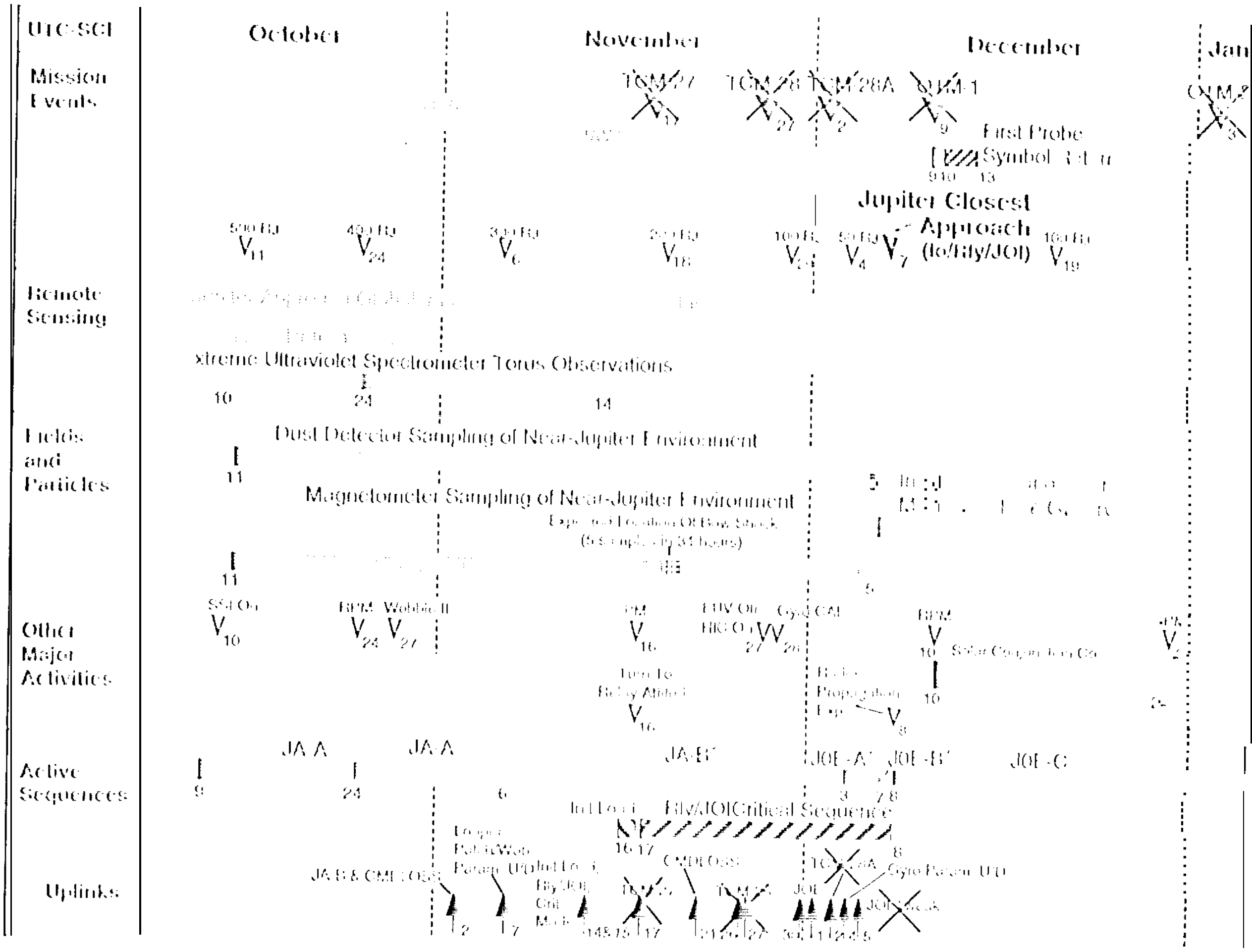

Figure 1. Approach/Arrival Timeline

figure out how to somewhat recover the Orbiter mission without it, and extend the computer storage of Probe data. This was when the Project had hoped to better prepare for contingencies that might occur within a few days of Jupiter arrival.

Incredibly on the very same day the spacecraft Recorder failed to rewind, an identical recorder in the ground testbed malfunctioned. These turned out to be totally separate problems, but the coincidence greatly compounded the troubleshooting. The testbed unit had broken the tape was pulled off the reel due to a circuit failure. Within one week, the troubleshooting tiger team had determined that, on the spacecraft, the tape may just be stuck and slipping on the capstans. On October 20th, the spacecraft Recorder was commanded to move the tape forward for a few seconds it worked! We were still a very long way from knowing what caused the problem. At this point a very painful decision was required. Until the Probe data was returned to Earth, the Recorder would be used only to record and playback the Probe data because of the paramount importance of the Probe data and Probe data record and playback required only the most benign use of the Recorder. Because recording the absolutely unique fields and particles data in the Io torus was equally benign, that recording was added at no significant risk. All imaging and other high-rate data had to be eliminated from the arrival sequence. Independent of the Probe considerations, it would have been foolish to risk damaging the Recorder before we could determine how to use it safely at the imaging rates (high tape speeds) for the ten satellite encounter Jupiter orbital tour. (The loss of the high resolution Io images was the biggest disappointment, but we may go back after the primary mission to get them.)

It has been conclusively determined that the tape is sticking to a "dummy" erase head that is only used as a tape guide in Galileo's Recorder. This sticking results in loss of tape tension and consequent tape slipping on the capstans when trying to run in reverse. After months of vigorous effort, the exact phenomena that causes the sticking is still unknown, although, some good candidates have been identified. In mid-March, the Project held a two day Workshop at JPL with a broad spectrum of tape recorder industry experts. They all concurred with the Project findings. Since the cause of the sticking is not known, we do not know how to prevent it. Accordingly, an operational strategy has been implemented that will always pull the tape forward to break the stick before running in reverse. Testing and conditioning of the Recorder on the spacecraft has further influenced operational procedures.

The Flight Software has been augmented to directly control some Recorder functions previously done autonomously by the Recorder. This will prevent the catastrophic failure that occurred in the Testbed Recorder and other potential problems. The new software also provides for detecting a stuck tape and

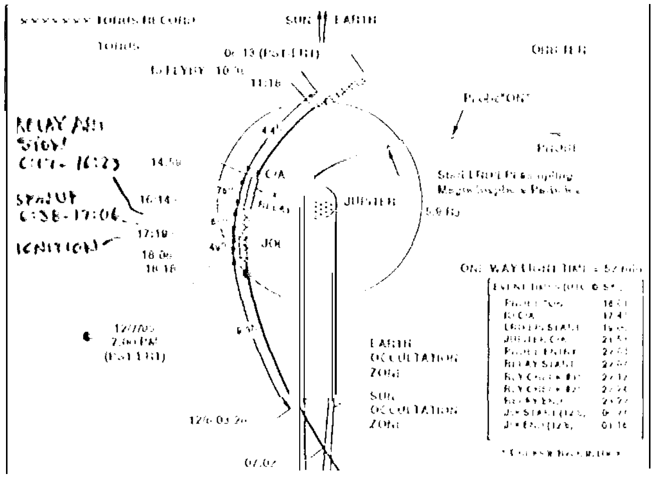

Figure 2a. Arrival Events

* 3 SIGMA

Event		PLANNED	OBSERVED
Io Flyby	Altitude (km) Time (UTC)	1000 / 937 17:45:44 / 17:45:53	892 ± 6* 17:45:58 ± .25*
Probe Signal	Relay Receiver "In Lock"	Relay Start + 5 min Relay Start +17 min	YES [✓] NO [ ] YES [✓] NO [ ]
JOI -0.1%!	Timed Min Burn [ ] Accelerometers [✓] Timed Max Burn [ ]	46 min 52 sec 48 min 37 sec 51 min 13 sec	48 min 59 sec
Spacecraft Status		Expected	
	Jovian Environmental Induced Events (PORs)	NONE	NONE
	Autonomous Fault Protection Actions	NONE	NONE
	Power Margin, Temp, Pressures, Torque	PER PREDICTS	ALL NORMAL
	Subsystem Operation	NORMAL	ALL NORMAL

Figure 2b. "Quick-Look Report"

stopping the Recorder in that event.

A very notable accomplishment was achieved by the Development Team within just two days after the October 11th anomaly. They devised a scheme for obtaining images by buffering them through the central computer without using the Tape Recorder. While this method is not anywhere near as effective as using the Recorder, it is infinitely better than no images at all and it was a priceless salvation when we thought the Recorder was broken. It was so remarkably good that the Orbital Phase 2 software development was suspended for one month to complete the preliminary design even after it appeared that the Recorder could be recovered. This capability development is continuing on a best efforts basis just in case the Recorder does fail during the orbital tour.

The decision to eliminate the imaging and other high-rate recording operations required a complete re-work of the spacecraft approach and arrival concurrent sequences. The rigorously bulletproofed and tested Relay/JOI critical sequence required only one-for-one replacement of five commands to accommodate the Io torus recording which in turn required several realtime ground commands for complete fault protection.

The greatly reduced concurrent arrival sequence enabled the expansion of the Probe data storage into the then unused sequencing memory so that the Probe symbols storage could be extended single-string to 73 minutes.

Elimination of the imaging also eliminated the optical navigation on Jupiter approach. The combination of superb DSN doppler tracking and an ingenious Navigation Team strategy enabled the successive cancellation of the three approach Trajectory Correction Maneuvers (TCMs), the Orbit Insertion delta-V update commanding, and then an essentially perfect JOI performance enabled canceling the two post-JOI Orbit Trim Maneuvers (OTMs). The strategy, which ultimately advanced the first in orbit satellite encounter (Ganymede-1) by one week, was developed to minimize the size of the OTMs—it surely did. Galileo went *ballistic* from JOI cutoff to Apojove. The changes to the approach events are illustrated in Figure 1.

The Orbiter performed the Io torus recording, the Relay Link, and the JOI flawlessly. The star scanner became radiation saturated as anticipated, but there was no other radiation disturbance as Galileo passed through by far the most intense radiation it ever will. Unlike Voyager, there were no POR's. Clearly, Galileo's designers did an excellent job in making it radiation hard.

Figures 2a and 2b are exactly (handwritten entries) as shown at the Press Conference within an hour after orbit insertion at 7 p.m. PST on December 7th. It was a time of the greatest jubilation. Everything had worked beautifully. The Radio Receivers on the Orbiter were in-lock on the Probe signal at both checkpoints[1], the 400N main engine burn was terminated by the accelerometers and the direct earth-based doppler tracking indicated only a 0.1% delta-V error, and all spacecraft telemetry indicated nominal status.

Several days immediately after arrival were particularly busy and critical as indicated on Figure 3. Propulsion pressures had to be verified before sending a "go" for spindown and there was considerable urgency in the first return of Probe data before Galileo's radio signal got too close to the sun for reliable telemetry reception. Serendipitously, elimination of the first orbit trim maneuver allowed the readout of the augmented Probe symbol data storage (from 39 to 73 minutes after relay start) a day before the prime data. This advanced by several days the determination that the Probe transmitted for 57.6 minutes and the depth of penetration

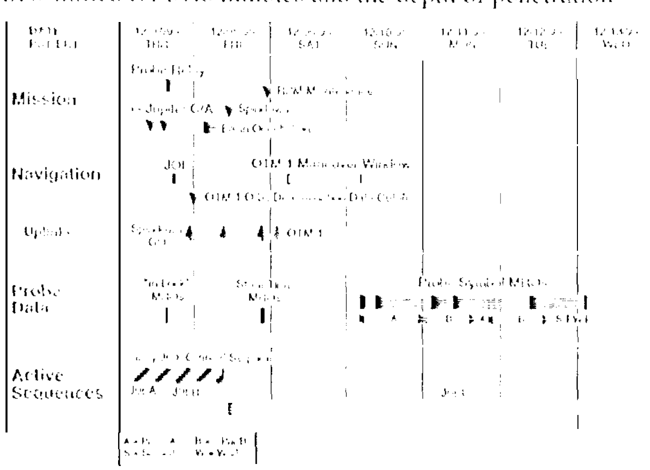

Figure 3. Post Jupiter Orbit Insertion Sequence of

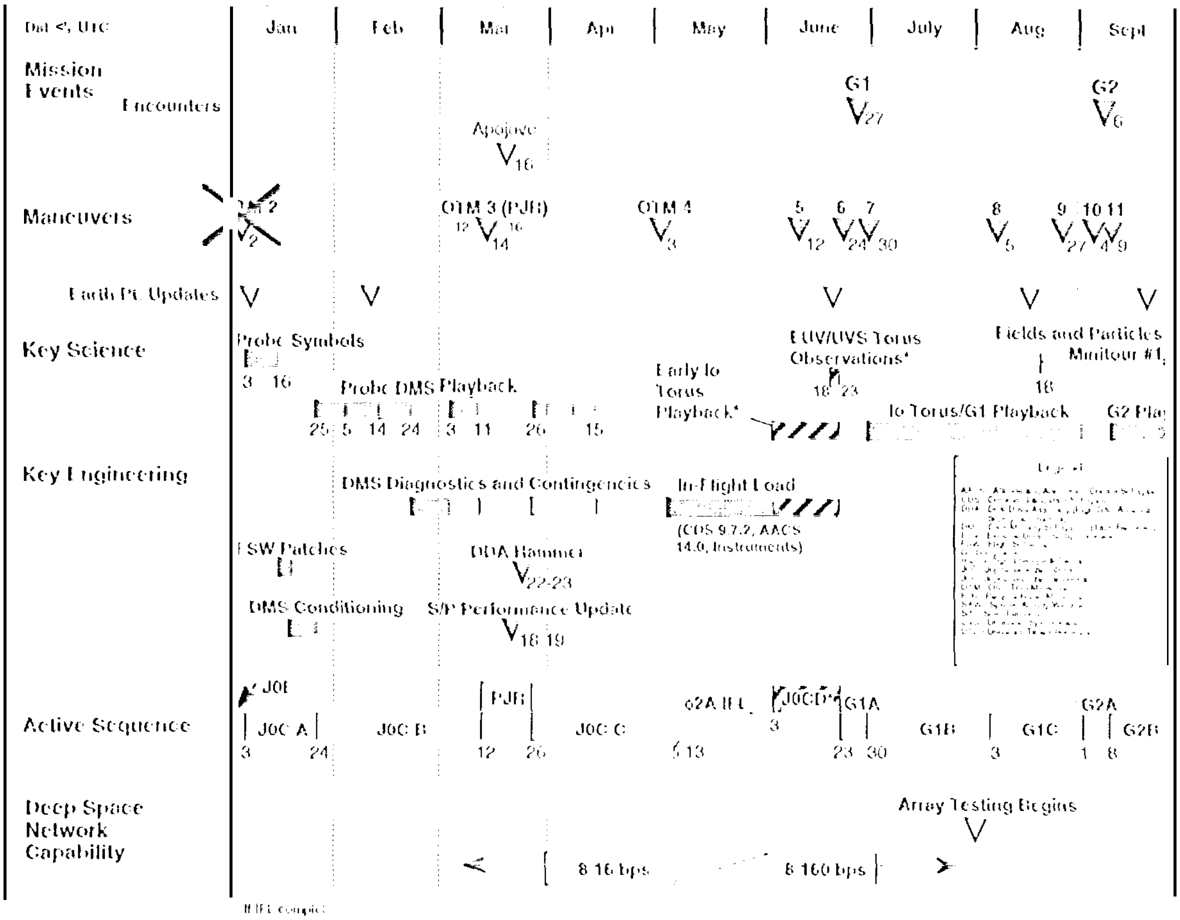

Figure 4. Galileo Timeline of Events (Jan 96 - Sept 96)

Figure 4 shows the major activities following arrival. The Probe Symbol storage was readout twice more for besting two out of three. Flight software (FSW) patches and Tape Recorder conditioning were added in order to safely playback the recorded Probe data, which was still the primary Probe data source.

The Perijove Raise Maneuver (PJR) was performed on March 14th raising perijove- the lowest point of the orbit- to 715,000 km above Jupiter to withstand the radiation for the upcoming eleven perijove passes during the orbital tour (first perijove at Relay/JOI was only 215,000 km). This was the third and final burn of the 400N main engine. The 378 m/sec maneuver- over half the size of the JOI- just about doubled Galileo's orbital speed at its then farthest point from Jupiter (apojove) and used two thirds of the propellant that remained onboard after JOI! Since the Orbiter Deflection Maneuver (ODM) in July 95, there existed concern that the helium pressurant checkvalve on the Oxidizer side of the propellant system may be leaking. At the end of PJR, the helium supply was immediately autonomously isolated to "trap" the Oxidizer pressure below the Fuel pressure to eliminate the threat of Oxidizer vapor migrating to the Fuel side. Unfortunately, the Fuel checkvalve apparently malfunctioned during PJR so the Ox pressure was higher than the Fuel pressure and the threat of migration remained. A painstaking review of the situation established that the potential quantities of diffused propellants in the respective pressurant lines given the recent helium infusion at PJR were far too small to produce any harmful reaction if mingling did occur. Accordingly, the desired electrical power margin and consequent propellant heating (power margin is shunted to propellant tank heaters) was commanded as needed for the orbital tour. The mission will be completed with the propellant feed in blowdown mode.

Over the past three years- in parallel with preparing for the precise delivery of the Probe and Orbiter to Jupiter, orbit insertion, and the capture and return to earth of the Probe data, and performing the second-ever spacecraft encounter of an asteroid and Comet Shoemaker-Levy 9 Jupiter impact observations- the Project developed extensive new software for the main spacecraft computers and most of the science instruments. And, after the tape recorder problems last October, more software was added to the new flight package so the central computer could make the recorder behave.

In May, the central computer (CDS) was completely reloaded by radioing every bit- literally every one and zero- of the new flight software package to Galileo. This software enabled the Orbital Mission. It was truly a complete brain transplant over a 400 million mile radio link. The new software was also radioed to Galileo science instruments and the attitude control computer.

The new CDS capabilities and major DSN enhancements were first used in June to return virtually all of the fields and particles data that Galileo recorded while flying through the Io torus on arrival day December 7th. These data

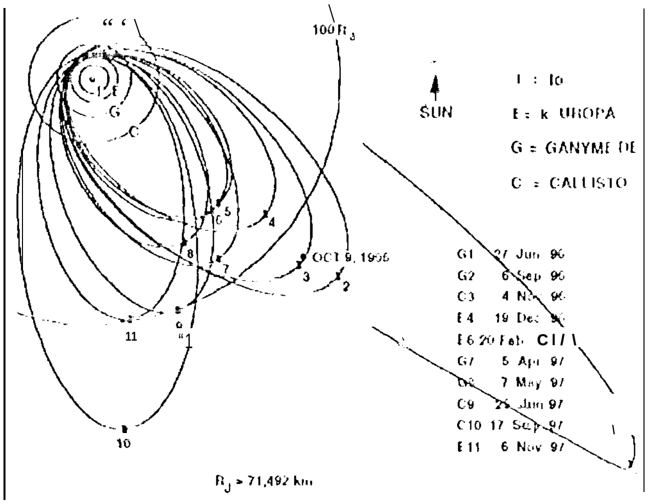

Figure 5a. Orbital Tour of the Jupiter System

are producing impressive findings. The already announced evidence of Io's iron core and magnetic field were obtained earlier from readouts of the Magnetometer itself and the Doppler data.

Ganymede-1, the first satellite encounter of Galileo's long-awaited Jupiter System orbital tour was a grand success-in many respects it was successful way beyond expectations! Galileo found evidence of a Ganymede magnetosphere, hints of an atmosphere, and Ganymede surface features that are absolutely mind-boggling. Truly stunning images of Jupiter, Europa, and Io were also captured. Already we have a great bounty of science data to apply to our three co-equal Galileo science objectives-the Jupiter atmosphere, magnetosphere, and satellites. These data will provide powerful insights into the Jupiter system as they are analyzed worldwide over the coming years. The spacecraft itself-including the tape recorder-performed perfectly throughout the entire encounter and continues to be flawless in the ongoing data return. Navigation was as spectacular as ever and used the brand-new, real-time, optical navigation image return at over 200 to 1 data compression. Altitude error was only 9 km!

The Ganymede-1 encounter marked two absolutely momentous milestones for Galileo-both a beginning and a completion. The science data marks the joyous beginning of the great bounty of science we will continuously reap from the Galileo Orbiter over the next year and a half. The successful encounter also marks a joyous completion-the recovery of the Galileo Orbiter Mission without its High Gain Antenna!

We did have some problems at the Ganymede encounter. The Energetic Particles Detector (EPD) instrument shut itself off before the encounter. It has now been determined that there is a flaw in the EPD internal fault detection logic. Workarounds are being used to operate EPD until a permanent patch is installed.

The Near Infrared Mapping Spectrometer (NIMS) became anomalous a day after Ganymede closest approach. After finding nothing fundamentally wrong with the instrument, its FSW was reloaded and started. NIMS has operated properly since. We have taken some precautions for NIMS at Ganymede-2 in the event NIMS has a transient problem associated with the

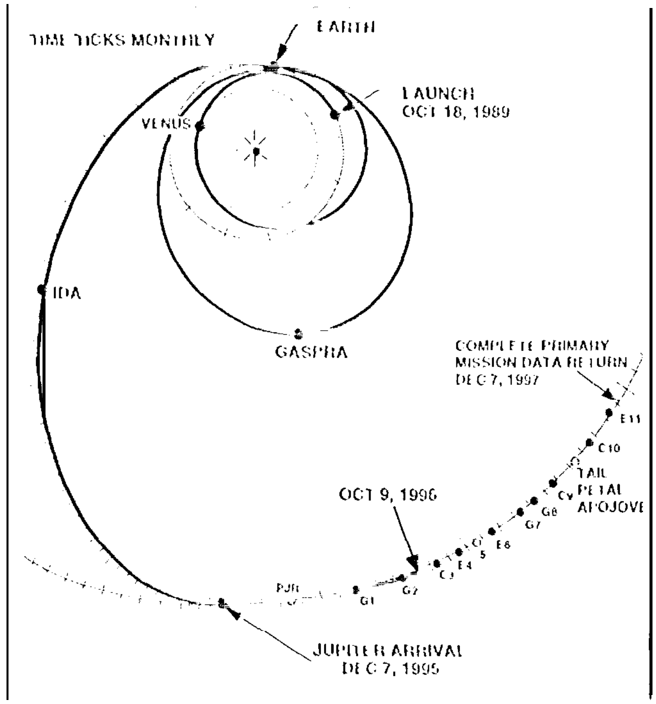

Figure 5b. Heliocentric View

near-Jupiter environment.

Well before the encounter, continuing testbed testing of the new FSW found a problem with the CDS handling of NIMS data playback from the tape recorder. Consequently, all the other data was played back first while this problem was diagnosed and a software patch developed. The patch was installed in July and the NIMS data was played back with a second pass through the tape recorder in August.

The Project is on a marathon now. By design, on June 27th, Ganymede's gravity reduced Galileo's orbital period from seven months down to just two months. There are nine more satellite encounters in the next sixteen months-three each with Ganymede, Callisto, and Europa! The finalization of the detailed spacecraft encounter sequences and playback sequences and frequent updates of the onboard playback tables is a continuous process on a Just-In-Time schedule to minimize cost and maximize responsiveness.

With its new brain, instrument, and attitude control computer software, and very major enhancements by the Deep Space Network (DSN) to receive signals ten thousand times weaker than originally planned, the Galileo Orbital Mission is off to a great start.

The current position of the Galileo Orbiter is shown in Jupiter-centered and Sun-centered space in Figures 5a and 5b, respectively. The second Ganymede encounter in September was also highly successful and it is described at the end of this paper. That encounter sequence began on September 1, five days before closest approach to Ganymede on September 6. The success of the encounter was especially gratifying, because on August 24th, a timing overrun in the central computer resulted in the CDS A-string going down and spacecraft safing. The Project team recovered full CDS operation and onboard science processing in five days of stunning all-out effort in

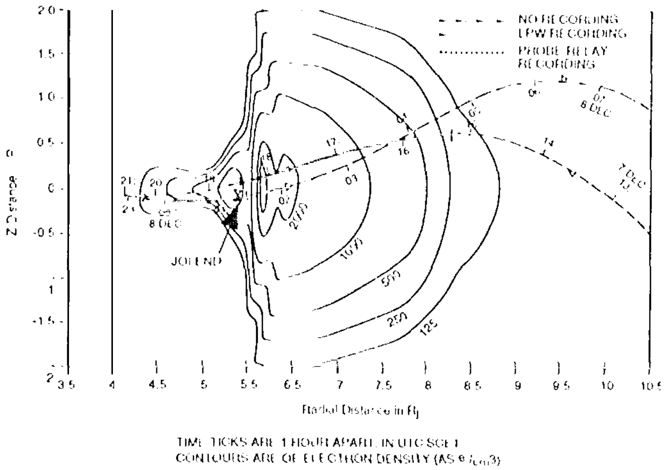

Figure 6. Io Torus Passage

order to perform the encounter.

2. Re-work Of Approach Science

The concurrent approach sequences had been developed to take full advantage of the rich science observing opportunities during the last few days and hours on approach to Jupiter. Opportunities included a 32,000 km nearly south polar passage of Europa, a near-equatorial 1000 km pass by Io, a very carefully crafted pass through the Io torus, observations of the Probe entry site, and distant Amalthea and Adrastea[3]. Space on the tape recorder was at a premium and the observations were integrated to take maximum advantage of this unique opportunity. Much of the recording required high record rates, up to 806 kbps, necessary to accommodate imaging and multiple instrument recordings. However, all through the design of this sequence, it was recognized that the recording and return of the Probe data was the highest scientific priority, and nothing was to compromise this.

Shortly after the Recorder (DMS) anomaly, while there was still very little understanding of how the DMS would perform, how it might be safely operated, or even what was wrong with it, clearly the only prudent course of action was to use the Recorder only in modes necessary and safe to acquire the Probe data. The entire science sequence was abandoned and the new plan was to record only the Probe data. At the time of the anomaly, the tape fortunately was positioned near beginning-of-tape, so it was possible to record on track 1 with no positioning of the tape required. Fortunately, the record format used for recording the Probe data was the lowest rate used by the DMS, 7.68 kbps. After further analysis, it was determined that a portion of the fields and particles recording that had been planned for the Io torus passage could also be safely accomplished. This recording is done at the same rate as the Probe data, and as long as the recording was limited to forward motion on track 1, little if any additional risk would be incurred. The final plan recorded about 3 hrs of fields and particles data, starting about 6.5 hrs before the start of the Probe relay, then paused for about 3.5 hrs, then 81 minutes of Probe recording followed immediately by another approximately 2 hrs of fields and particles recording. Figure 6 shows, on a scale of distance out of the magnetic equator versus distance from Jupiter, the path of the Galileo Orbiter superimposed on contours of constant electron density in the torus. Figure 7 shows a standard encounter trajectory plot with the torus and regions of recording indicated.

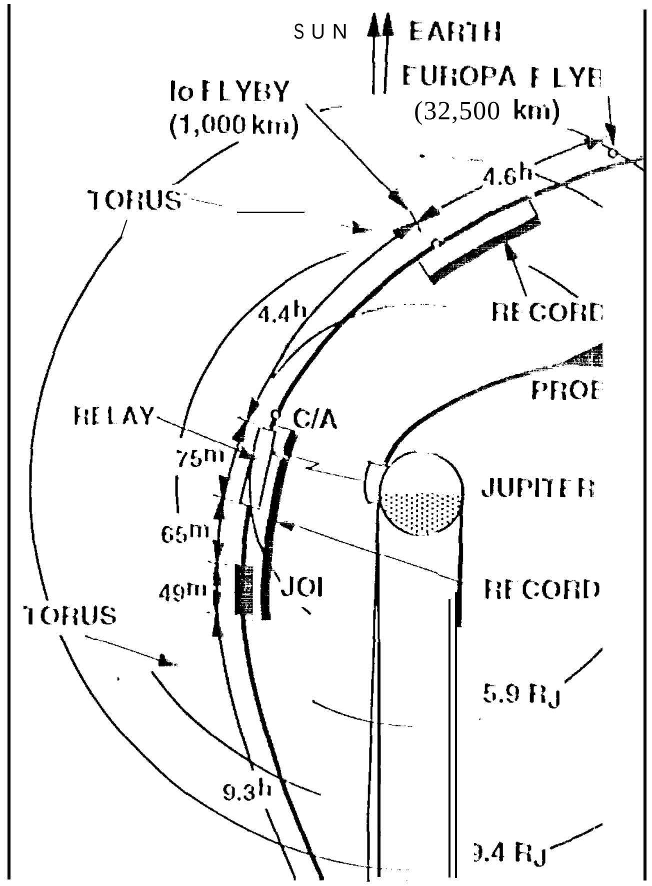

Figure 7. Torus Recording

The entire data acquisition and return was accomplished without any problems. The Probe data was returned mostly in February and March using the Phase 1 FSW. The fields and particles data was returned in the first three weeks of June using the new Phase 2 software (see "Orbital Flight Software Loading"), completing just prior to the start of the first Ganymede encounter sequence. The loss of the approach remote sensing data was a significant disappointment, but the decision to forego it has been very clearly exonerated. Based on subsequent analysis and the results of both flight and ground DMS testing and characterization, there is little doubt but that the tape would have stuck during high speed recording in the approach sequence. This would have had a significant potential for causing permanent damage to the tape, little if any Orbiter science data would have been obtained, and no recorded Probe data would have been collected.

3. Relay/JOI Operations and Performance

Following the successful Probe Release and ODM in July 1995, the focus of the Project riveted on preparations for the Probe relay data acquisition, Jupiter Orbit Insertion (JOI), and the Orbiter science sequence that would start in early

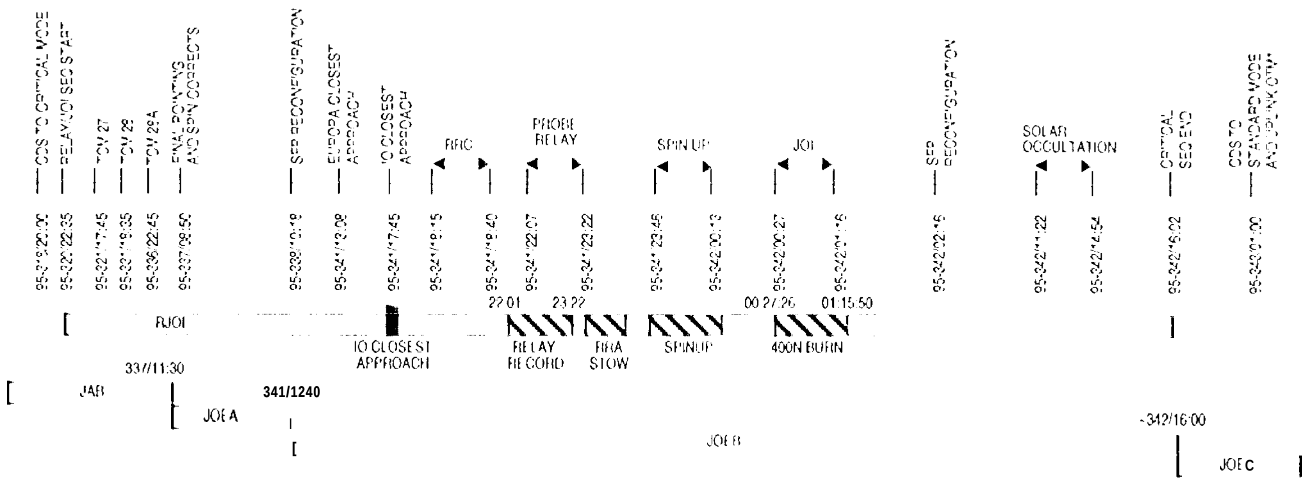

Figure 8a. Relay/JOI Timeline

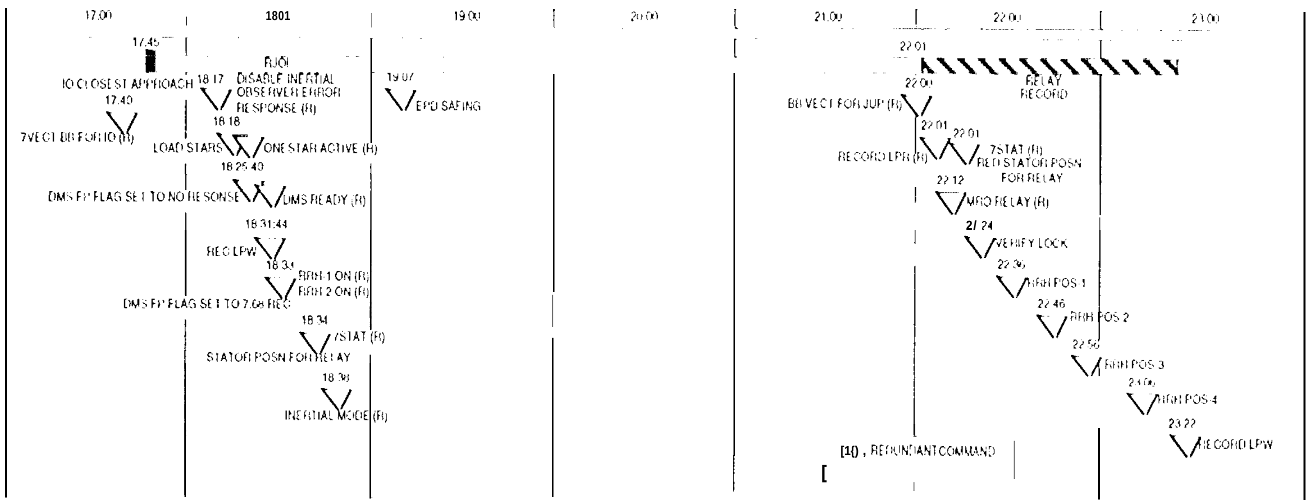

Figure 8b. Relay Expansion

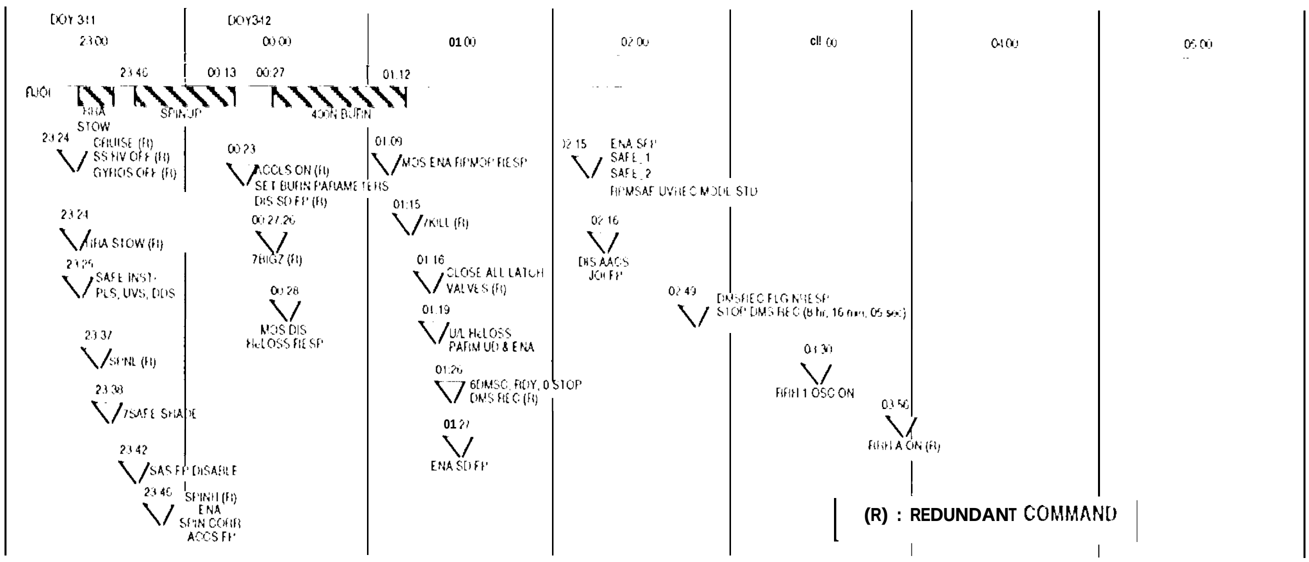

Figure 8c. JOI Expansion

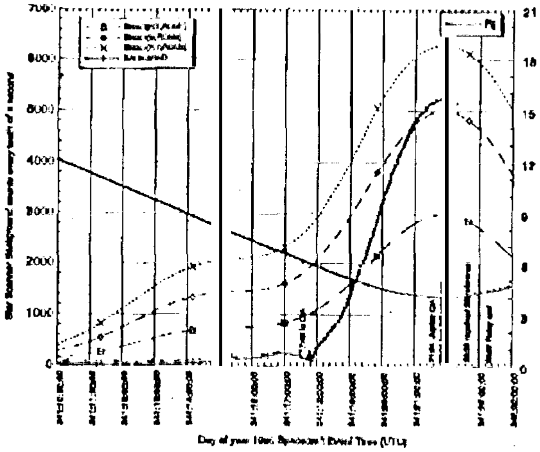

Figure 9. Star Scanner Radiation

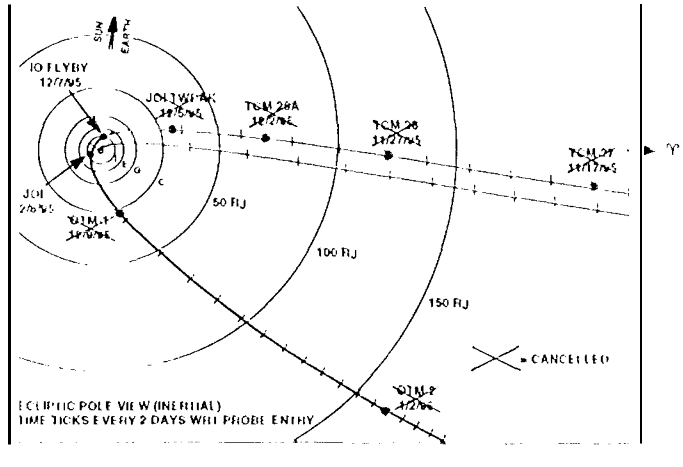

Figure 10. Jupiter Encounter Maneuvers

October 1995. Figure 8a shows a summary timeline of the key activities occurring during the approach and encounter.

In September and early October, iteration 4 of the Relay/JOI critical engineering sequence was going through final testing and validation for a November 14 uplink to the spacecraft. The DMS anomaly on October 11 required another iteration along with a repeat of the sequence test program and validation process. In addition, all of the approach and encounter science sequences had to be updated and revalidated to remove the DMS recording activities except for the F&P low rate recording of the Io Torus data. The critical engineering sequence changes were kept as simple as possible to remove the DMS rewind and record the Probe data in the safest way for the recorder. In addition, the Probe symbol storage area in CDS memory was increased to allow collection of an additional 33.2 minutes of Probe data (73 minutes total). The Probe symbol storage technique was the backup to the DMS. Another precaution, i.e., sending backup real-time commands, was also taken to protect the DMS in the event the background sequence terminated. All of these late changes created a significant amount of new work that had to be completed in November to support the uplink schedules.

The Relay/JOI critical engineering sequence execution started on November 15 and ended on December 8. Figures 8a to 8c show an overview of the activities controlled by the sequence. Running concurrently with the critical engineering sequence were the science sequences labeled JAB', JOI}A', and JOEB'. The sequences executed beautifully with no radiation induced upsets or spacecraft faults due to the hostile Jupiter environment. The Relay Radio Antenna (RRA) was initially positioned in clock angle on November 28, 1995 in preparation for a gyro drift calibration (the cone angle was positioned much earlier on August 21, 1995). As part of the Relay Readiness Configuration, the RRA was commanded again to the proper clock position approximately 3 hrs 33 min prior to the start of the relay; this command resulted in a 0.5° correction to the pointing. To protect against certain fault cases, the RRA was redundantly commanded in clock a third time just prior to the relay recording. The four RRA cone repositionings required to stay pointed at the Probe all executed as planned. The DMS recording of the relay data and storing of probe symbols in CDS memory all worked as planned. The Probe relay data was captured for 57.6 minutes as the Probe descended in the Jupiter atmosphere. The JOI following the Probe relay executed flawlessly; the accelerometer controlled shutdown of the 400-N engine resulted in only a 0.13% overburn, and burn time was well within the spec of ±4%. The AACS and RPM subsystems performed nominally and happily none of the additional fault protection that was added to the spacecraft was called.

The Probe delivery was well within the requirements as shown in Table 1. The sequence design provided data in real-time that confirmed that the Probe signal was acquired and in lock. This confirmation was only at two points in time during the relay, i.e., 5 minutes and 17 minutes after nominal relay start. When the Probe Engineering Team reported over the voice net that the Probe signal was acquired, everyone was estatic. The big question of how long the Probe transmission continued had to wait for the Probe symbol data receipt.

One of the telemetry measurements received during the encounter was the Star Scanner background radiation level. This was of great interest for general spacecraft health and operation concerns, and also for the ability of the Star Scanner to stay "locked" on Canopus. Canopus was to be used as roll reference for pointing the Probe relay antenna in the event the gyros turned off for any reason[1]. The radiation level rose sharply following the Io flyby and reached a level of 5200 pulse counts per 1/10sec at closest approach. The Star Scanner lost lock (SEQID routine) on Canopus during the relay for approximately 35 minutes. Figure 9 shows the Star Scanner observed radiation counts during the encounter and shows that the radiation at encounter went above a RDM of 2 (Radiation Design Margin). The Star Scanner hardware was designed to a RDM of 3, but clearly did not have that capability since it "lost" the brightest available star.

The telecommunications performance on the low gain antenna was an issue of particular concern since the encounter was 17 days prior to solar conjunction where both maximum range and solar scintillation effects occur. The angle between the spacecraft and the Sun was 8.6 deg as viewed from the Earth at encounter. The new DSN Block V receivers were utilized to provide the needed telecom

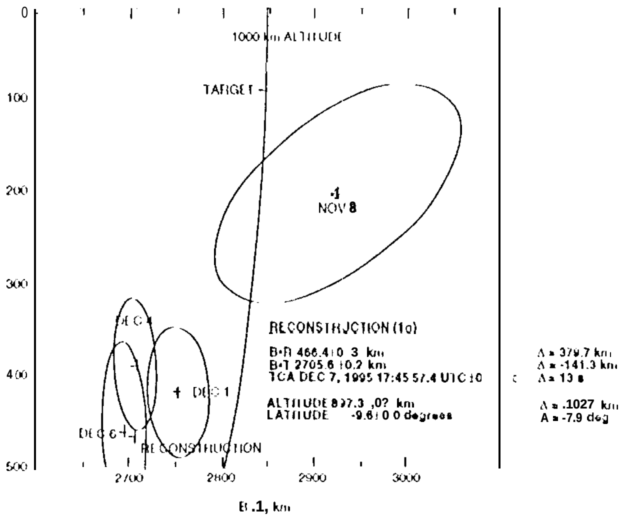

Figure 11. Io Target Plane

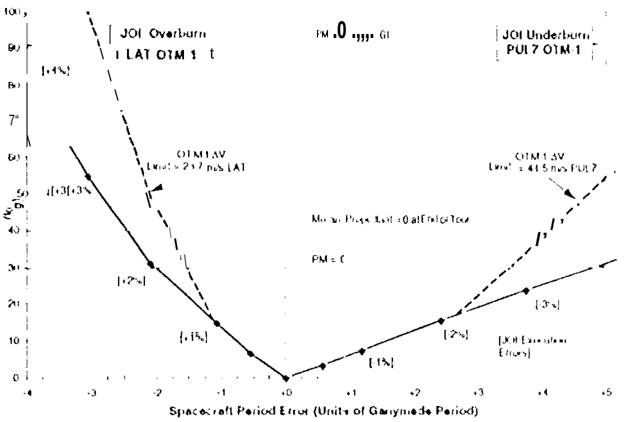

Figure 12. Cost to Maintain Nominal Tour

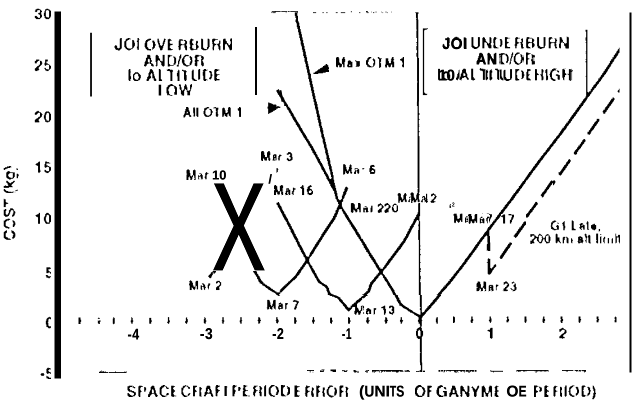

Figure 13. Orbit Trim Maneuver (OTM)-1 Contingency

performance for telemetry and radiometric tracking. Solar scintillation effects on the telemetry started at the end of October 1995. Aproximately 1.5 days before Jupiter encounter the downlink signal was changed from fully suppressed carrier mode (nominal configuration for best performance) to residual carrier mode. In the presence of solar scintillation, this mode provided continuous data return during Relay/JOI and subsequent first Probe data symbol return.

The longstanding Jupiter approach navigation plan included optical navigation images and 2-way doppler data types, and maneuvers TCMs 26, 27, '28, and 28A (see Figure 1 ()). Orbit determination knowledge improves on approach to Jupiter. TCM 26 was 0.98m/s and corrected the ODM execution errors. Prior to the DMS anomaly on Oct. 11, the trajectory target had an Io altitude of 1000km. The DMS anomaly resulted in all of the optical navigation images being deleted from the plans. The optical data was of particular value for controlling the Io encounter conditions for the remote sensing observations of 10. Since all of the remote sensing observations were also deleted due to the DMS anomaly, the 1000 km altitude navigation targeting requirement could be relaxed.

Table 2. Trajectory Estimate History with 1σ Uncertainties

Data Cutoff Time (days before Io)	TCM Supported	TCA* 12/7/95 UTC	(km)
Target		17:45:44	1000
-114 (01)91)	?6	41:55 ± 29	-X(K) ± 429
-27 (01)94)	27	45:39 ± 11	1084 ± 126
19 (01)95)	28	45:40 ± 12	1080 ± 145
-6 (01)96)	28A	45:53 ± 2,1	93-/ ± 36
-3 (01)9-/1'2)	29 (JOI)	45:58 ± 0.8	888 ± 27
+ 0,01 (OD 100)		46:00 ± 0.1	892 ± 2
+55 (Recon.)		45:57.4 ± 0.0	897.3 ± 0.?

* Time of closest approach

TCM ?"/ was scheduled 20 days before encounter. The orbit determination solution at 2-/ days out (data cutoff) had an arrival time 5 sec early and an Io flyby altitude of 1084 km. The maneuver was waived off since the flyby miss was well less than the 1-sigma uncertainty, i.e., 126 km in altitude.

As Galileo approached Jupiter, the trajectory solution continued to migrate toward 10 and down in the B-Plane as shown in Figure 11 Table 2 shows a history of the 0 1) solutions and the uncertainties[4]. With no optical navigation images, the B.R knowledge is most affected and the uncertainty is much higher, i.e., 1-sigma optical values of 32 km expected. The 01) solution at 19 days out for TCM 28 had an altitude of 10S() km, with a 145 km 1 sigma uncertainty. Again the maneuver was waived off. At the 6 day out data cutoff for TCM 28A, the Io flyby altitude migrated below 1000km and the time of arrival drifted later by 9 seconds from the target.

Contingency navigation strategies were being formulated by the Navigation Team and discussed at the TCM Design Team for cases where there was a big post-JOI period error. In particular, big JOI overburn arid/or a substantially low Io flyby would result in such a low orbit period post-JOI that the tour would be compromised due to the large propellant usage needed to correct the trajectory. The first such (discussions occurred on Oct 26, 1995. on November 29, 1995, the Project approved this contingency strategy. Figure 12 Snows the propellant cost to recover the nominal tour given a post JOI period error in units of Ganymede period (approximately 7 days). Figure 13 shows the contingency strategy costs. For the Io altitude low case, the arrival at G1 could be earlier by 7-day increments with very little propellant cost. On December 1, 1995, the strategy was accepted and the TCM 28A was waived.

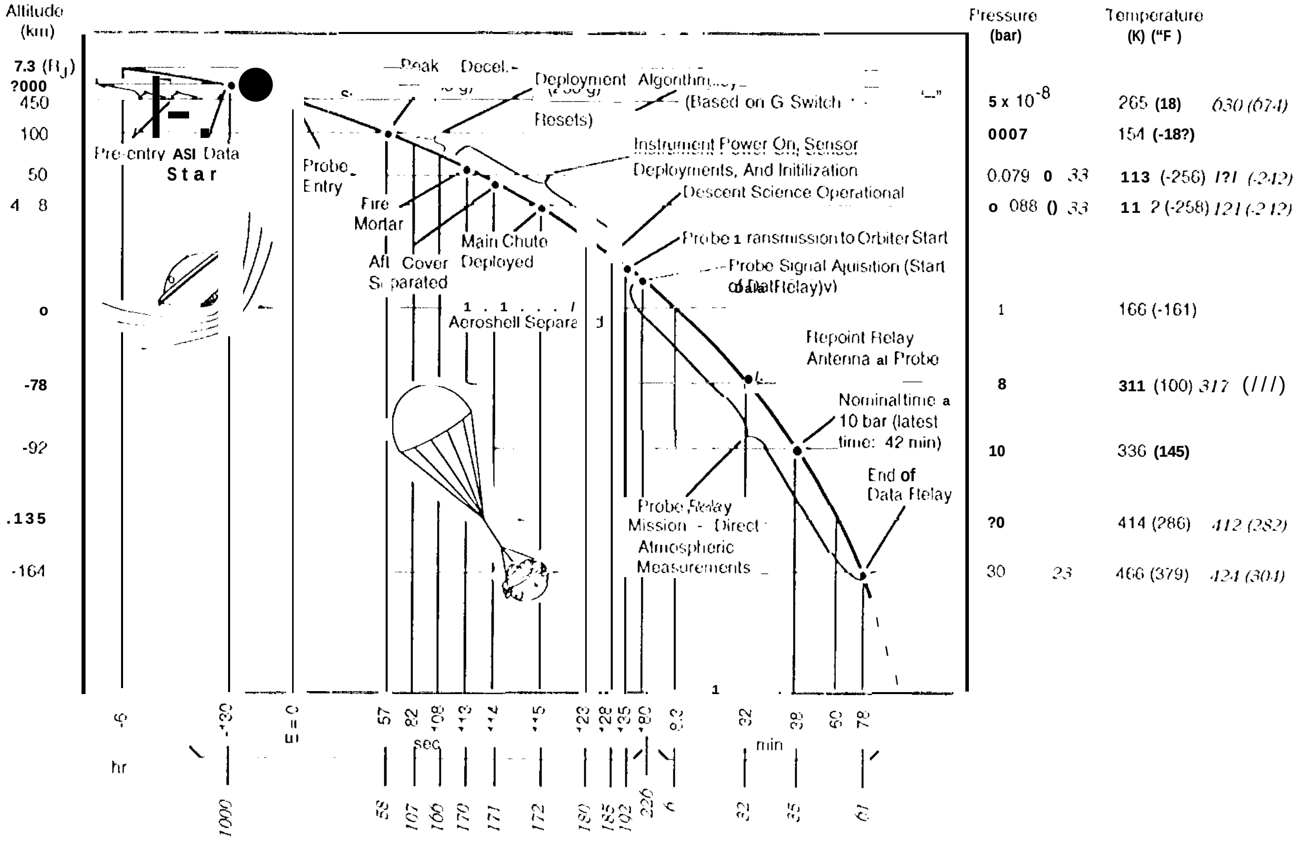

Figure 14. Probe Descent Profile (Predicted vs. Actuals in Italics)

Shortly after, the JOI tweak was also canceled. The Io altitude solution dropped as low as 888 km. The reconstructed Io flyby conditions are shown in Table 2.

Approach maneuvers TCMs 28 and 28A and the JOI tweak to the onboard maneuver parameters were all waived off with the contingency strategy to encounter Io at a lower altitude and advance the G1 encounter date one week to June 27, 1996. This strategy allowed eliminating spacecraft activities and thereby reduced risk and also minimized the use of propellant. OTM 1 and 2 were also waived off because of the excellent JOI performance, the Io flyby altitude translating into a lower post-JOI period of approximately one Ganymede period, and the decision to arrive at G1 encounter on June 27. The next maneuver required after JOI was PJR.

Contingency plans were developed for anomalies on the spacecraft and the ground. Potential spacecraft faults were identified and classified into categories, i.e., do nothing, handle in real-time, and pregenerate command files. The only contingency commands pregenerated were for a "critical mode" CDS bus reset recovery. CDS bus resets have occurred numerous times during the mission and resulted in one of the two CDS strings going down[7]. See Table 3 for a list of the contingencies considered. In addition, Project policies relative to restarting science sequences were established, as well as the latest time prior to relay that an attempt to bring up a down CDS string would be made, namely approximately 3 days before relay.

4. Atmospheric Probe Performance and Science Results Summary

Figure 14 illustrates the predicted entry and descent events in altitude-time space with key actuals added in italics.

4.1 Pre-Entry

A reconstruction of the Probe sequence of events based on the time of Relay telemetry signal acquisition indicates that the Probe timer timed out only 15 seconds early after its 155 days count-down, at 16:00:58 UTC, 6h 3m 45s before entry. The first timeout closed the relays to depassivate the Li/SO_2 batteries, conditioning them for descent operations. After about 8 seconds, the main power relays closed, applying power to the main bus which powered on the Probe A-string Ultra-Stable Oscillator (USO) and the A-string Data and Command Processor (DCP). The DCP executed its pre-sequenced commands to begin configuration of the pre-entry science instruments, the Lightning and Radio emission Detector and the Energetic Particle Instrument (LRD/EPI), which share electronics.

The first 5 hours of pre-entry operations consisted of a series of timeouts where short series of commands were executed. At the conclusion of each timeout, the DCP coast timer was reset, the DCP was commanded to its low power mode and the timer counted down to the next timeout. The USO remained powered on throughout. Twice the DCP was

Table 3. Candidate List of Fault Scenarios

- CDS DESPUN TRANSIENT BUS RESET - CDS STRING DOWN (STRING RECOVERY POSSIBLE)
- CDS HARD FAULT (HLM, LLM) - CDS STRING DOWN (STRING 1/0 ST)
- SYSTEM FAULT-INDUCED SAFING - OTHER THAN CDS DESPUN TRANSIENT BUS RESET
- CDS MEMORY FAILURE - CDS STRING DOWN/EFFECTUAL DOWN
- AACS MEMORY FAILURE
- RRH OSCILLATOR OR RECEIVER FAILURE "TO COME ON
- INCORRECT CDS DATA MODE
- INCORRECT DMS (TAPE RECORDER) CONFIGURATION
- MISPOINTED RELAY ANTENNA (STATOR)
- NO SPACECRAFT CARRIER MODULATION (TMU, "B" STRING DOWN OR UVREC)
- LOW GROUND-RECEIVED SIGNAL. Srl'Rl\NG't'll-S-1.O (TWTA FAULT)
- OSAD/ASAD IS NOT ENABLED
- LOSS OF STAR DATA - STAR SCANNER FAILURE (SEQID)
- SPIN DETECTOR FAILURE
- E/P DISABLE VULNERABILITIES - RPM O/P
- UV REC (POWER/THERMAL)
- POWER RELAY SWITCH FAILURE

powered on only to command a reconfiguration of the LRD/EPI and it was not until the fourth power-on sequence that any data were collected. Snapshots of LRD/EPI data were collected at 5.1, 4.2, and 3.3 Jupiter radii, each for about six minutes. The last timeout occurred 1h 4m 57s before entry and continuous EPI data were collected from 2.4 Jupiter radii to the 101101 the atmosphere.

Final preparations for entry began 28m 16s before entry when the Neutral Mass Spectrometer (NMS) pump was turned on to ensure a vacuum in its quadrapole analyzer; B-string DC '1' was powered on, enabling redundant Probe operations; the Atmospheric Structure Instrument (ASI) was turned on and calibrated; and the Nephelometer (NEP) was turned on, calibrated, and then turned off.

4.2 Entry

At 16m 38s before entry, the Probe began storing entry mode data for the ASI, collecting acceleration and heat shield data. These data were stored in a recycling memory buffer to ensure collection of the data during the deceleration and heating pulses.

Probe entry was defined to be when the Probe reached an altitude 450 km above the 1 bar pressure level. A reconstruction of the Probe event timing based on the known time of telemetry lock-up indicates that entry occurred at 2:04:44 UTC. Two mechanical G-switches sensed the Probe deceleration pulse and the timings between their actuations and resets were used to calculate when to start descent operations.

4.3 Descent

Descent operations began 2m 4"/s after entry when the Probe data format changed to descent format and all instruments were turned on. The thermal battery was activated to power the pyrotechnic events, which included deployment of the pilot chute, severance of the cables to the aft cover, release of the aft cover which pulled out the main parachute, severance of the cables to the forward heat shield, release of the forward heat shield, and deployment of the NEP arm. Data transmission to the Orbiter began 26s after the start of descent operations, and the signal was acquired by the Probe receivers on the Orbiter 34s later. 80s after the start of descent operations, the data stored during pre-entry, entry, and early descent began to be interleaved with the real-time data. Over the next 43 minutes, these memory data were read out twice. The Probe reached its primary mission goal, the 10 bar pressure level, 35.3 minutes after entry and continued to transmit data after the pressure had reached more than 23 bar, 61.4 minutes after entry.

4.4 Relay

The Orbiter was configured for Probe relay well before entry. The Relay Radio Hardware (RRH) USOs were powered on and the relay antenna was positioned for the start of descent 9 days before entry; the receivers were powered on 16.4 hours before entry. Three minutes before predicted entry, the Orbiter data format was commanded to the low rate Probe format and the tape recorder began recording data. At signal acquisition, the storage of Probe data was begun in the CDS RAM to back up the tape recorder. To allow for real-time verification of relay, snapshots of the receiver data were transmitted to Earth at E+8m and E+20m. These snapshots showed that both receivers had locked up, but little more was known for several days. The relay antenna was repositioned four times during relay to follow the Probe. After 81 minutes, the Orbiter data format was changed, receivers were turned off, relay antenna stowed, and configuration for JOI began.

4.5 Engineering Performance

The time of Probe signal acquisition (stored on-board the Orbiter) was read out the day after entry and found to be about a minute later than expected. It was not immediately known whether this was due to a late arrival of the Probe or whether the signal acquisition had been delayed. Within a week of relay, all the Probe data stored in the CDS RAM had been read out, and although the data were noisy and had outages due to noise from superior conjunction, the overall mission success could be verified: pre-entry and entry data were stored and returned properly, all instruments came on and produced valid data; and the link had been maintained for 57.6 minutes. Over the next several months, every Probe data bit was verified and all but 3.3 minutes of the receiver data (collected mostly for radio science) returned and verified.

4.6.1 Deceleration Module

The Probe's deceleration module had two major functions: to provide thermal control during cruise and coast and to protect the descent module during the entry. For both of these, the deceleration module performance was excellent.

Temperatures during cruise and coast were maintained at the nominal 0°C level except during intervals when the Orbiter was turned for HGA anomaly operations.

The performance of the heat shield during entry was primarily determined by the survival of the Probe and the successful operation through relay. Data were collected during the entry, however, by the ASI, showing that the deceleration profile of the Probe was very much as expected, having a peak deceleration of 228 g's. Analog Resistance Ablation Detector (ARAD) sensors were embedded in the heat shield and were used by the ASI team to calculate the heat shield shape and mass loss during entry. These sensors showed that the mass loss were very close to the predicted value (90 kg) but less material ablated from the nose of the Probe heat shield, and more from the side, when compared against expectations[5].

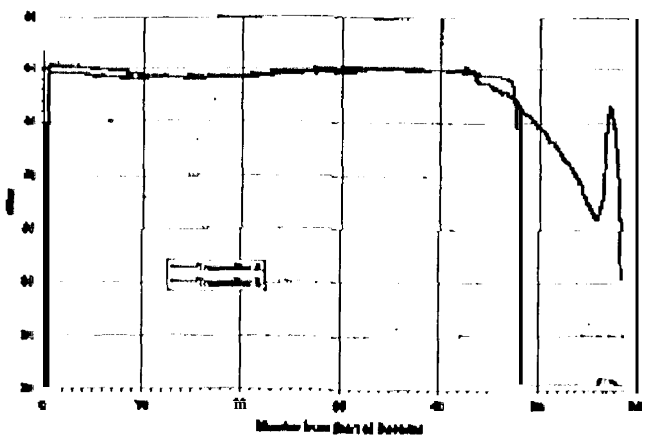

Figure 15. Probe Transmitters Output Power

4.7 Descent Module

The Probe descent module performed very well, collecting and transmitting the first in-situ data from the atmosphere of an outer planet. There were two performance anomalies, both of which had an impact on the science as discussed below.

4.7.1 Data and Command

All commands that could be verified were verified (many were redundant) and there were no indications of any command anomalies throughout the Probe mission. Data storage and formatting also was flawless. Both G-switches activated and reset as expected, however, it appears they were cross-wired, the times for the one switch being recorded as the other and Vice-vmsa. Since the times of these G-switch activations were used by the DCP to calculate the time to start descent operations, this resulted in a 53 second delay in the start of descent. One of the science objectives was to begin descent operations at a pressure level of 0.1 bar, ensuring that data collection above the visible ammonia clouds would occur. The first descent data, however, were in fact not collected until the pressure was about .45 bars. This impacted the cloud instruments and the Wind measurements, which wanted to correlate their data to the remote sensing Of the cloud tops.

4.7.2 Power

The Probe's power system, consisting of Li/SO_2 batteries and thermal batteries, performed perfectly. Bus voltages were maintained above required thresholds throughout the mission and the mission ended before the battery voltage showed any drop-off. The thermal batteries, which powered the pyrotechnic events, operated as required and all pyrotechnic events fired as expected at the start of descent.

4.7.3 Communications

The Probe communications system performance is illustrated in Figure 15. The output power of the redundant transmitters remained fairly constant until 51 minutes after entry when the B-string transmitter output power dropped suddenly. The A-string communications string did not show a sharp drop off until about 11 minutes later, and when its power dropped, the mission ended. The A-string output power did show an unusual signature over the last 12 minutes of the mission, slowly dropping and then rising again. One possible explanation for the unusual signature in A-string power is that the transmitter, which was in a sealed box, experience structural deformation from the increasing pressure. The sharp power drops at the end of each strings operations are believed to be due to exciter failure due to the increasing temperature.

4.7.4 Thermal

The Jovian atmosphere temperature ranged from below -120°C at high altitudes and low pressures, to over 150°C at the end of the mission when the pressures reached about ?4 bars. The Probe descent module was not sealed; it had a chimney in the aft end to allow the pressure to equalize with the exterior atmosphere. The thermal protection system was passive, consisting of thermal blankets and baffling to reduce air flow, and was designed to keep the instruments and engineering subsystems between their operating temperature limits of -20°C and +50°C through 48 minutes of descent.

Flight results showed that the thermal protection system did not provide sufficient isolation, as almost all instruments and subsystems experienced temperatures outside of their operating range during the primary mission. Although the atmosphere temperatures were very close to expectations, temperatures of some instruments reached -50°C and were as high as 100°C after 48 minutes. This has caused several of the instruments to require calibration testing of their spare equipment to understand their data at the flight temperature profile. Preliminary analysis of the anomaly suggests that the convection on the Probe was much higher than expected, probably due to increased air flow through the Probe through the unsealed aerofairings, turbulence, and buffeting, none of which had been simulated in ground testing.

4.8 RRH

The Relay Radio Hardware (RRH) on the Orbiter consisted of a paraboloid antenna and two receivers. The receivers acquired the Probe signal well within their required time limit and maintained solid lock on both data streams with Only one exception throughout relay until the output power of the Probe transmitter dropped. The single exception occurred on B-string at 47 minutes after entry when the data became very noisy and could not be processed through the ground computers for about 1 second. The signal quality recovered solidly after this incident and it does not appear that this glitch was caused by the same phenomenon that ended the link several minutes later. No data were lost as the A- and B-strings were fully redundant at the time.

The antenna was controlled in clock angle by the Orbiter AACS using gyros for roll stabilization. The cone angle was set well before relay to the initial angle required for the first 32 minutes of relay. Beginning at 32 minutes, the antenna cone angle was stepped once every 10 minutes to follow the Probe. There were no antenna anomalies throughout relay.

4.9 Science Results

The LRD/EPI measured high energy charged particles trapped in Jupiter's magnetic field as the Probe approached Jupiter. New radiation belts consisting of helium and heavier ions were discovered that extended to within 0.4 Jovian radii of the atmosphere. This was the first time a spacecraft had been this close to Jupiter and could measure the radiation levels in this region.[6]

The entry site was imaged in the infrared from Earth on the day of encounter within an hour of entry. Higher resolution images of the entry site were unavailable due to the tape recorder anomaly on the Orbiter, and solar angle constraints for Hubble Space Telescope. The images showed the entry site was at the edge of a "hot spot", an area where it is believed there are very few clouds and the heat of the planet interior radiates outward.[7]

The nephelometer (NEP) data confirmed that the entry site was relatively cloud free. The clouds visible from Earth, the ammonia clouds, are expected to be at a pressure level of less than 600 mbar. Due to the late initiation of descent operations, the NEP did not have an opportunity to detect the ammonia cloud layer. It did detect a very thin cloud in a region models indicate might be ammonia hydrosulfide clouds, at a pressure level of 1.5 bars. Water clouds were expected at a pressure level of about 5 bars, but no water clouds were seen at all in the NEP instrument.[8]

Consistent with the NEP results, the Net Flux Radiometer (NFR) did not see the energy flux patterns that would indicate thick clouds, and in fact, NFR data suggests that the water levels were significantly below solar, much lower than predicted by pre-encounter models. The NFR did not see any signatures of the ammonia hydrosulfide clouds, but did see solar radiation fluxes associated with the uppermost ammonia clouds that the NEP missed.[9]

The LRD data is also consistent with a water free region at the entry site. The only mechanism known to produce lightning is water clouds, and no local lightning was indicated by the optical sensor and the radio emissions detector sensed only very distant lightning. Overall, the LRD detected a global lightning rate of about one tenth of Earth, but the energy in each twit was about ten times that of typical Earth lightning bolt.[10]

The ASI data included the deceleration and heat shield data taken during entry which was used to calculated the upper atmosphere structure. Data indicate that the upper atmosphere is much denser than pre-Galileo models predicted. During descent, the ASI measured acceleration and turbulence, pressure and temperature. The ASI pressure sensors were particularly sensitive to temperature and uncertainties remain large at this time due to the temperature anomaly. The temperature/pressure profile data seems to indicate the atmosphere is stable, a rather unexpected result.[11]

There were two instruments which measure the atmospheric composition. The Helium Abundance Detector (HAD) accurately measured the ratio of helium to hydrogen. This value is important in understanding planetary evolution, and the measurement taken, 23.8% by mass, indicates that Jupiter's overall composition remains similar to the original cloud that formed the solar system. Voyager found that this ratio is reduced significantly at Saturn, implying that Jupiter and Saturn have evolved along different paths.[12]

The NMS measured the amounts of elements and compounds through atomic mass units of 150. The NMS found that carbon and sulfur have two to three times greater relative abundances than in the Sun. This implies that comets and other small bodies have impacted Jupiter throughout its history and deposited extra material. Oxygen is another element expected to be enhanced by planetesimal impacts, but it was found to be

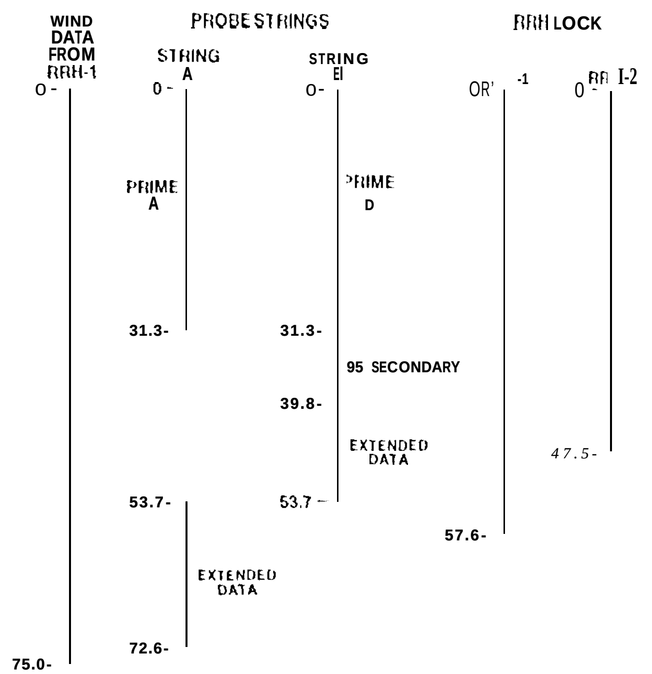

Figure 16. Probe Symbol Data Storage

greatly depleted. As oxygen on Jupiter is tied up with the hydrogen to make water, this value is consistent with paucity of clouds detected by other investigations, but the reason for its depletion remains unknown. The last few NMS data points give a hint of a considerably increased water abundance at depth as much as twice solar. However, these data remain to be verified because of uncertainties in the calibrations and high instrument temperatures occuring at the end of the mission. If this increase in water at great depth is verified, then the mechanism for drying the atmosphere in the entry region to this depth is a major new science question.[13]

The radio signal frequency of the link between the Probe and the Orbiter was used to calculate the winds during Probe descent. The Doppler Wind Experiment (DWE) found that the winds were higher than expected, reaching a value of about 180 m/s (400 mph), and remaining high throughout the descent. The wind profile is used to examine what is driving the weather on Jupiter, and the continued high winds at deep levels suggests that the energy driving Jupiter's weather comes from its interior.[14]

5. Probe Data Return

The original plan to provide functionally redundant methods to return the Probe data was to relay the data direct to Earth in real-time via the Orbiter High-Gain Antenna (HGA) and simultaneously record it on the Orbiter tape recorder (DMS) for later replay. With the failure of the HGA, the plan was modified to use the CDS memory for redundant storage for about half of the Probe symbol data, with storage limited by available memory. (The term "Probe symbols" refers to the actual convolutionally encoded data bits coming from the Probe, but exclusive of the additional receiver information that was also stored on the DMS.) Then, when the DMS anomaly occurred less than two months before arrival, the plan was again modified. The decision was made not to use the DMS for high rate remote sensing recording during the approach and encounter. (See section 2.) This action reduced the memory requirements for the encounter sequence enough to allow almost complete storage of one string of the Probe symbols in the CDS. Figure 16 shows the final plan for storing receiver data for the DWE (only every other measurement was stored) and selectively storing the data from both of the Probe telemetry strings. Extended data refers to the additional storage that became possible after reducing the Orbiter encounter observing sequence. The full set of Probe data was successfully recorded on the DMS. Most importantly, both telemetry strings were recorded for the entire time for protection against dropouts on either string. Additional data recorded on tape, but not stored in the CDS due to memory limitations, included all the DWE measurements, ASI receivers data, and data quality bits on the Probe data generated by the RRH receivers.

The plan for the stored symbols was to return them three times. Since the symbols did not contain the extra information added by the receivers that was in the DMS recorded data, the time to return them was relatively minimal, and the extra returns provided an effective way to insure that all the data was returned accurately. The first return was completed prior to the expected loss of communications when the Orbiter passed through solar conjunction during the last half of December. This return was facilitated by the fact that the first OTM planned for after orbit insertion was not needed, thus allowing the Probe symbol return to be advanced by one day, and thus completing the first return, including the extended data, prior to loss of telecommunications caused by the approaching conjunction. There were only some small data outages caused by near-conjunction induced noise on the Orbiter to Earth link.

The second return of Probe symbols started after conjunction. About 2/3 of this return was lost due to a spacecraft safing event caused by an oversight wherein a fault monitor flag was not properly reset after JOI. The third return was completed without incident on Jan 16. The data that was not returned during the second readout was returned later, after the DMS recorded data return was complete. No Probe symbols were stored for the time interval from receiver lockup plus 47.5 minutes to 53.7 minutes, as shown in Figure 16, because during this period, Probe telemetry string B was the source of the symbols to be stored, and its transmitter quit at lockup plus 47.5 minutes. That made this section of Probe data the highest priority for the DMS data return.

A period of time had been allocated after the completion of the Probe symbol return to exercise the DMS and condition the tape prior to beginning the recorded data return, which was scheduled to begin on January 24. The DMS data return was to start at the beginning of the Probe data and continue straight through to the end, i.e., FI-FO. However, during the tape conditioning activity, the tape stuck under circumstances that had been believed to be unlikely to lead to sticking. This led to a decision to return the recorded data in a prioritized order rather than time order. Given that most of the Probe data was now on the ground via the successful symbol return and it might take considerable inflight testing and characterization of the tape recorder to be able to do the Orbiter mission, it was prudent to provide opportunity for these contingency recorder operations at the possible expense of not returning the lowest priority Probe data.

The recorded data judged to be highest priority was the period from 47.4 to 53.7 minutes, since this was not available in the stored symbol data as mentioned earlier. Second priority was from 31.3 to 47.4 minutes, since this was single string only (B) in the stored symbols. Third priority was the early descent data from -2 to 10 minutes, which was also of high interest for the radio science investigation. Fourth priority was the remaining descent information, 10 to 31.1 minutes and 53.7 to 63.1 minutes. This carried the data return well beyond where the symbol data indicated that both receivers were out of lock, but this was a deliberate action to insure that all data that might be available was recovered. The lowest data priority was from the period of 7 minutes before receiver lockup to 2 minutes before. This data was of potential interest for the radio science experiment, because it provided additional opportunities to assess the receiver noise characteristics prior to signal acquisition.

The final result was that all of the DMS recorded data was returned from signal acquisition -2 minutes to +63 minutes, with only very minor data outages that were not recovered. For the data stored in the CDS, all of it was returned at least twice, almost all of it three times, and in some instances, it was returned four times. The only data that was a prospect for returning that was not was the DMS data from -7 to -2 minutes, and this data was of questionable value, since it could only aid in receiver noise characterization that was also covered in the -2 minutes to signal acquisition interval that was returned. The overall end result is that 100% of the information in the Probe data was recovered.

6. Tape Recorder Anomalies and Recovery

The Galileo tape recorder (DMS), built circa 1981, is a [ccl-lo-l-ccl recorder which stores up to 900" million data bits on about 1800" feet of mylar (ape. The DMS has 4 tracks (1 and 3 move forward, 2 and 4 move in reverse) and can be operated in various modes at several speeds ranging from 7.68Kbps (0.8 inch/see) 10806.4Kty)s (78 itlcllcs/see). CDS derived tape position information is basal on DMS motor shaft rotation. Normally, it accurately reflects the tape position. However, it for any reason the tape fails to move when commanded, and the motor shaft tur as, this derived position is no longer coIIL'et, The actual tape position is then unknown until it is derived from data previously recorded on the tape or by positioning the tape to its leader al either end.

When the DMS became mission critical following the 1 IGA failure, its usage was specifically restricted to required health maintenance and important science of opportunity. The frequency Of health maintenance tape conditioning activities was reduced to about every 90 days consistent with the updated flight operating rules developed by J]']. and the DMS manufacturer (ODETICS). Tape conditioning basically consisted of moving the tape back and forth end-to-cad at 806.4kbps and finally positioning it near the ccatcl-of-tapc (('0-1').

6.1 Anomaly Descriptions

On October 11,1995, after being commanded to perform a rewind al 806.4kbps to the Beginning-O f-Tape (BOT) in preparation for the Jupiter -approach image playback, telemetry showed unexpected tape position leadings. Instead of the CDS derived tape position indicator decrementing and stopping al 110-1', the telemetry readings continuously decremented to a minimum count and then rolled over to a count of 16,384 counts exceeding 7,177 are beyond the physical tape length. Because of the low downlink telemetry data rate (I o bps), the anomaly was not identified for nearly 3 hours after onset. Within an hour after identification, it was decided to transmit a ground command (61)MSK) to "safe" the DMS by commanding it to Ready Mode- tape is stopped but power is on. The J)MSK command also prevents the CDS from issuing subsequent DMS control commands. (After lock out, another 1)MSK command is required to enable the CDS to issue commands to DMS.) Unfortunately, because of the delay in identifying the problem, operational problems al Goldstone that prevented re-configuring for high-power commanding before set, and because the high power transmitter was broken at the rising station (Canberra), the DMS "safe" command was not sent for neatly 15 hours after the onset Of the anomaly. Once received, the DMS properly responded to the ground command by going to Ready Mode. Subsequently, as an added precaution, a ground command was sent to terminate the CDS stored approach science sequence 10 prevent issuance of subsequent 1)MS commands. Additionally, commands were sent to disable the DMS unique system fault protection which would autonomously move the tape forward and backward in case of a DMS power on reset (1'01<) fault.

Within hours of the flight anomaly, in an ongoing ground test, the *flight spare* DMS in the testbed experienced an anomaly while executing a portion of the Jupiter arrival close-encounter science sequence. Immediate troubleshooting of the flight spate unit revealed that the DMS was no longer functional. Within a clay, reconstruction of the testbed scenario indicated the recorder "stalled" thru some lo\v-speed commands, moved very slightly at a few high-speed commands and ran "free" suggesting stretching and then breaking the tape. The flight and spare DMS were identical and both were being commanded by identical, new CDS software. The coincidence of these faults required the most careful scruting. The most important action now was to determine if the flight recorder was working, i.e., can the tape be moved.

The anomalies could be the result of errors in the new software controlling the. CDS-DMS command/telemetry interface, errors made in the stored sequences, or actual faults in the DMS. On October 14, 1995, after substantial ground retesting and analysis of the approach science stored sequence and MRO verification of the CDS-DMS interface night software, the flight anomaly was confidently isolated to the 1)MS. By October 18, it was determined that the flight tape may have stuck somewhere in the transport or reel and then slipped on the capstans.

On October 20, ground commands were scat to determine if the tape could be moved. A short (10- second) playback forward (in the opposite direction of the fault) tape motion was commanded at the lowest speed. Proper motion was verified via motor current and other telemetry. Fortunately, the tape was not broken and the DMS may be recoverable. At the outset, it was not clear which direction to try the move. Mechanical considerations led to the belief there \vas more authority to move tape off a nearly fail reel than vice-versa ("downhill" vs. "uphill"). Tape tension is maintained by a negator spring that applies a fixed torque to both reel nabs. Tape tension alone provides the drive friction at the capstans (i.e., no pinch rollers).

The playback data indicated that the actual position, determined by data on the tape, was the same location where the October 1 1 anomaly occurred, suggesting the tape had slipped at that location for the entire 16 hours before ground commanded 10 stop. Because of a concern for tape abrasion during the 1() hour slip, ground commands were sent on October 24 to "bury" the possibly weak slip spot under about 25 wraps of tape. The wrapping action was performed in playback mode at the lowest tape speed, Proper operation was again verified via motor current and tape position.

A comprehensive review of all tape position data \vas initialed to determine if the October 1 1 flight anomaly was a first time event or whether unnoticed tape position errors (off predict) had occurred earlier. Review of the flight data revealed that the first tape position error occurred in July 1995. Another was observed in September 1995. The July 1995 error went unnoticed, because at that time, data was only being "spot checked" for gross problems . This "spot check" analysis approach was instituted years earlier as part of the Project's re-engineering cost savings effort. Furthermore, focus was on the upcoming critical Probe Release activity (mid-July 1995) and the first firing of the propulsion subsystem main engine (late

July 1995). And then the focus was on the essential Relay/JO1 sequence desi gn update development effort and there was no opportunity or motivation to review in detail the July/September DMS data.

Because both the flight and ground DMS anomalies could be related, the investigation into the ground unit failure was also performed with high priority. When the spare unit was opened, the tape was found to be pulled off the reel at the hub equivalent to the expectation of a broken tape. Subsequent failure analysis revealed that the ground unit failure was the result Of a marginal circuit design causing a relay to fail to transfe r and autonomously remove power from the drive electronics when the End-of-Tape (EOT) location (leader) was sensed.

Additional precautions now had to be taken with the flight unit to avoid the failure observed in the flight spare unit. Furthermore, it was considered prudent to avoid unwrapping the tape wrap covering the possibly damaged piece Of [ape. Consequently, the usable tape length was reduced about 305 feet (240 from BOT end and 65 from EOT end) still leaving about 1500 feet of usable tape. This scheme avoids going onto the leader should the DMS be stopped via the on-board autonomous fault protection which was being designed while fault investigative actions were proceeding. Three weeks after the anomaly the exact cause of the DMS flight anomaly was still unknown, although mechanical faults seemed to be the most likely candidates. The leading candidate was that the tape was sticking to a sapphire dummy erase head used to guide the tape. The dummy head is "downstream" of the capstans when the tape is moving in reverse; when the capstans try to "push" the tape toward where it is "anchored", tape tension is lost and slipping ensues unabated. Exactly why/how the. sticking occurs was and still is unknown. At [his point, the Project decided to only operate the DMS at its lowest speed until the Probe data was captured on the tape because it was concluded that the prospects for additional anomalies arc greater when operating at high speed, and only the lowest speed (7.68kbps) was required to meet all the requirements for Probe Relay data capture and return; and there was no prospect for understanding the anomalies and developing a reliable/safe DMS high-speed operation plan in time for Jupiter arrival day.

6.2 Pre-Jupiter Arrival Flight Activities

Letting the tape sit unused for approximately four weeks before Jupiter arrival was now thought to be risky, particularly, if the DMS failure was duc to lack of motion for a protracted time. Therefore, it was decided to incrementally move the tape forward for several seconds at the lowest speed on Track]. The tape was moved three times in this fashion on November lo, 16, and 21 to provide added confidence that the DMS would work r c.list›l y for recording the Probe Relay data On 1 December "/. The DMS worked flawlessly for each incremental move and for all the Relay/JO1 record/playback activities.

6.3 Long-Term Trouble Shooting Activities

Well into 1996, the JPL/ODETICS Tiger Team continued its vigorous efforts to thoroughly characterize and fully understand all elements of the DMS, including tape chemistry, mechanism design/margin, electronics design/margin, and operational interactions. A comprehensive Failure Mode Effects Analysis (FMEA) was performed. Increased emphasis was placed on characterizing the effects Of aging and low usage by testing with similar tape recorders, specifically the flight spare Magellan unit, which has (ape from the same lot as Galileo and is very similar to the Galileo unit. A GEOTAIL transport unit which uses different tape and electronics was also used for testing. The flight unit also underwent a suite of characterization tests.

A special DMS workshop was convened at JPL in mid-March 1996 which included about forty NASA and industry experts On tape recorders, tape, mechanisms, and electronics. The experts acknowledged that tape sticking is well-known throughout the industry and agreed with the Tiger Team that the dummy erase head is the most likely site for tape sticking. There was no consensus as to why/how sticking was occurring. Several of the experts agreed with the Tiger Team that the sticking anomalies may be the result of not enough recorder usage. They commented that nearly all tape recorders are used "constantly" and arc Only idle for short periods of time (days), compared to months for the Galileo DMS.

The team presented the following stick models to the workshop:

(1) Debris adhesion - caused by ferric oxide debris particles interacting with the polymer tape/oil.

(2) Jo blocking - caused by an extremely smooth (glass-like) surface condition at the tape-sfi[]l]hirc head interface that enables n Molecular bonding. The more tape across the head, the smoother the sapphire head surface becomes.

(3) Electrostatic force - created by electrical tribology charges caused by the tape moving across the sapphire head. Opposite polarity charges can be generated in the sapphire head and tape. Charge in the tape is caused by mechanical stress.

It is possible that one or a combination of the model options may be able to explain ail the observed slicking anomalies. It became increasingly evident that whatever was going On may be ameliorated by moving the tape end-to-end at intervals significantly shorter than the aforementioned 90 days. The flight and ground data suggested that intervals shorter than a week may be optimum but that every 3 to 4 weeks may be adequate.

6.4 Post Arrival-Day Activities

After arrival day DMS operations, the (ape was not moved for 40 days until January 16, 1996. During the 40-day period, a conditioning/characterization test suite was developed. On January 16, the tape was moved forward in playback mode for 40 seconds on Track 1 ; motor current and other telemetry indicated normal operation. The day before, two new autonomous fault protection algorithms were put in place. Onc algorithm, the slip monitor, consists of monitoring the DMS servo lock (reading tape position" from the *tape*) status and issuing a DMS ready mode command if the servo lock status indicates out-of-lock in excess of a preset amount of time. This algorithm protects the tape from protracted slipping and possible damage. The other algorithm, preserves the CDS-DMS command interface in the presence of a CDS string down fault. Because the DMS can be connected to only one of the two CDS strings at any time, if that string went down (many CDS faults can bring a string down), there would be no way to command the DMS to the safe ready mode. This algorithm functionally switches the DMS to the other CDS string and commands the DMS to the safe ready mode. In addition to loading the new fault protection, special DMS test sequences were loaded to perform upcoming characterization testing.

On January 17, 1996, the tape was moved back to near BOT at 7.68kbps for nearly its entire length in preparation for tape characterization exercises to begin on January 18. Because some earlier ground tests suggested the prospects for sticking may be reduced if an appropriate cool-down time (defined as running at 7.68kbps) was used, various cool-down times were tested. The January 18 test suite was to characterize sticking after various cool-down times (15 minutes, 30 minutes and 45 minutes) and operating speeds, to perform and verify a 5-second forward tape unstick operation (in case the tape. stuck) and perform four end-to-end tape conditioning passes. On January 18, during the. first of five 1 00.8kbps (1 O ir~chcs/see) planned activities, *the DMS slip monitor tripped.* The DMS was autonomously commanded to ready mode, as designed. This 100.8Kbps exercise was the first higt]-speed operation of the DMS since the October 11, 191)5 anomaly. The tape had stuck in less than 2 seconds after stopping subsequent to being moved continuously at t 0 inches/sec for 34 minutes. This was a big surprise because it was believed the tape could not stick when stopped for only a few seconds. After analysis of the flight data, the test sequence was terminated to prevent any damage threat to the DMS that may be caused by continuing. It was then decided to do no further DMS characterization/ conditioning until after playing back the highest priority recorded Probe data- the most benign operation, i.e., lowest speed, forward only! (See''I'r()tJc I)atti I{ctIlrII''). Subsequently, it was decided 10 perfol-in the earlier aborted tape conditioning passes at the lowest speed (7.68kbps). On February 29, during the conditioning, another big surprise occurred. On the first conditioning exercise pass, after running at the lowest speed (always thought not to cause a stick) for nearly the entire length of tape (--7 hours) the tape stuck! *This was the first stick anomaly observed at //It lowest speed.* Now, it was becoming evident that the tape stick ing may trc function of many parameters such as tape speed, amount of tape passed over the dummy erase head, idle time between successive tape motions, and tape not used for a long time. In every case, the flight data showed that the tape could always be unstuck by moving forward at the lowest tape speed.

More flight tests were conducted in late April 1996 to characterize tape "re-sticking" using wait times of 2 seconds, 2 minutes, and 4 minutes before doing an unstick. It was now believed necessary 10 let a stick "cure" for some]I]irlutcstw.fore breaking it loose, otherwise, the. tape would immediately "re-stick." It was essential to determine a reliable tape reversing strategy, i.e., locally defeat the stick mechanism before moving in reverse. The wait time (4 minutes) was chosen based on the shortest wait time already inherent in the upcoming Ganymede encounter sequence. The tests were performed at t 00.8kbps and resulted in the tape sticking almost every time after an end-to-end tape pass. In every stick, except (me, the tape did not re-stick after being unstuck by moving forward at the lowest speed after the wait. All the tape sticks occurred at [ape locations that had not been used for many months. In the one case, the tape re-stuck during a direction change immediately following an unstick action that had only the 2 seconds wait.

6.5 Satellite Tour Operations

The new Orbital Phase CDS software contains a number of additional capabilities for both normal and faulted DMS operations. One of the new capabilities included adding marker zones at both ends of tape on all four tracks and having CDS command track turnarounds when these are detected thus precluding the EOT (BOT) detection failure that destroyed the testbed unit. The (100 tic) marker zones result in a usable tape length reduction of about 240 ft at BOT end (maintains the 25 wraps) and about 65 ft from EOT end (about 1500 feet of usable tape remains). Another capability was the merging of the slip monitor fault protection with the derived CDS tape position indicator to ensure the DMS is stopped if: 1) the tape slips longer than the preset time or 2) if the tape moves more than half-way into a marker zone. Several other protection capabilities are also incl uded which provide enhanced robustness.

About ?.5 days prior to the start of the Ganymede encounter sequence, via a specially designed sequence, another tape conditioning exercise was performed. This exercise, using playback mode at 100.8 kbps, consisted of four nearly full tape passes. The conditioning was purposely planned to go into the marker regions to plow tape debris away from where science data recording is planned, Telemetry indicated the DMS worked perfectly based on motor current profile and tape position data and no slip monitor trip. Because the DMS is essential for the encounter science, a DMS recovery contingency plan was developed in case the DMS slip monitor did trip during the tape conditioning exercise.

A heuristic mathematical tape stick prediction model has been developed incorporating all apparently key DMS usage parameters. It successful ly "predicts" all the observed DMS sticks and the "observed" no-stick operations. All sequences are now routinely checked with this model as a further protection against sticking. Tape time in prick (r"ccl), speed, tape across head each run, etc., are parameters.

6.6 Tape Conditioning Plans

Project plans currently call for performing two standardized tape conditioning exercises every orbit, one post-encounter near apoapsis and another pre-encounter, compacting within a day or so from the start of the encounter data recording sequence. Generally, the maximum time between conditioning exercises will be about 30 days. Based on ground and flight evidence, the current plan is considered adequate to reduce significantly the prospects for tape sticking.

Tape conditioning activities were performed on July '2S and AOgLISI31 in preparation for the Ganymede-2 encounter 011 September 6.

6.7 Ganymede Encounters

The Ganymede encounters on June 27 arid September 6 were performed using the completely new CDS and science flight software and new DMS flight operating rules based on the current knowledge of flight and ground test data. The sequences were designed based on the premise that the tape can stick and can always be unstuck with a 7.68kbps forward motion. It was essential that the sequences be designed to avoid slicking prior 10 moving the tape in reverse. Therefore, the sequences included minimum wait times (Ready) before [he. CDS autonomous unstick action. The 1)MS worked flawlessly during both the encounters and all data was recorded. The recorded data from G1 was returned and the DMS worked perfectly. Currently, the recorded data from the G2 encounter is being returned and the DMS is winking perfectly.

7. Tape Recorder (DMS) Loss Contingency

At the outset, the largest set of possible causes that might have explained the flight DMS anomaly was made up of things which could mean total loss of the recorder for the remainder of the mission. Because of (his, final work on the orbital operations or Phase 2[2], flight software (FSW) was suspended and the development team refocused as a tiger team 10 attempt the design of a spacecraft software set, called "Phase 3", which would allow a mission to be performed without a tape recorder. Phase 2 remained suspended for a month in order 10 complete the target Phase 3 design even though two weeks into the design, it appeared the flight DMS was recoverable. This section briefly describes the design. Part of the design is now being built as a background task during the Galileo orbital tour, as a contingency.

The primary objective of the Phase 3 design was to provide a way to get images (SS1) without the DMS. The Photopolarimeter Radiometer (1'1'1<) also did not have any real-lillle science capability in Phase ? and therefore would lose all science return capability with the loss of the recorder so it too was a priority. These Phase 3 capabilities needed to be available in time for the Ganymede 1 (G I) encounter in early July 1996. A secondary objective was to provide enhanced science return capability for other instruments where possible.

The design team quickly converged on an approach which was based upon the then nearly complete and very modular Phase 2. software design. This approach preserved the new, enhanced downlink capabilities (already built into Phase 2 and extensively ground tested) and limited the magnitude of the code changes to something that might actually be possible to complete in time for the (; 1 encounter. A brief list of the changes 10 be in place by the G1 encounter follows.

Command and Data Subsystem (CDS):

- Delete all co(lc associated with recording, play back, DMS control and fault protection (about 42 kbytes);
- Delete all inactive sequence memory (32 kbytes) but expand the CDS-A string active sequence memory from 8 kbytes to 12 kbytes;
- Add the space freed up by the code and sequence deletions to the Phase 290 kbytes Multi-Use Buffer (MUB) to expand it to about 160 kbytes;
- Add the capability to process SS1 images in real-tiillc. This consisted Of passing the small blocks (8x8) of image pixels from the instrument CCD directly through the Integer Cosine Transform (ICT) compressor within the Attitude and Articulation Control Subsystem (AACS) and then into the MUB;
- Add a new PPR Real-time High-rate Science (RHS) capability;
- Improve NIMS science return by replacing the Phase 2 real-time capability with a new NIMS RHS capability which would be more similar to the Phase 2 NIMS record/playback capability;
- Provide augmented AACS attitude information pickup to support the new NIMS and PPR capability.

AACS:

Modify the AACS FSW to increase background processing capability (i.e. - ICT compression) and decrease the Cruise-to-Inertial mode transition time. The first of these would allow ICT processing with gyros powered on (not allowed in Phase 2) and the second would allow more science acquisition during encounters by reducing transition wait times.

After the above initial capability was in place, two optional paths existed for further enhancements: (1) Rapid SSI raw image readout directly to the MUB (before ICT processing) and (?) new RHS modes for the UVS and PWS instruments, plus new higher rate Real-Time Science (RTS) pickup for the EPD, MAG, and }'1 .S instruments.

The rapid SS1 raw data readout directly into the MUB capability (before ICT processing) was considered the higher priority activity since radiation hits to the SS1 images (luring the long dwell time in the CCD during the slow (several minutes) readout during ICT processing through AACS were expected to severely limit the size of the images that could be returned. This capability was not includ cd in the GJ package, because the FSW team was not sure at the time that it was even feasible (still an open issue.) and thus did not think that it could be completed in time for the encounter.

If the rapid SS1 raw data readout [o the MUB was found to be feasible, it alone would be completed for the next FSW upload and the expanded 1{}1S/1{'1'S capabilities listed in (?) above would not be done. Otherwise, only the items in (2) would be Completed.

After the completion of the Phase 2 FSW, the decision was made to begin developing the Phase 3 FSW for both CDS and AACS. This development is being done as a low level background task (Phase 2 maintenance/repair being a higher priority) as a contingency against the possible future failure of the tape recorder. Only the ss1 direct ICT-to-MUB and PPR capability restoration are being included in this development (no SSI raw-to-MUB or RHS/RTS enhancements). Changes to the ground system to support the Phase 3 FSW arc being deferred until needed since they arc relatively minor.

8. Propulsion System Issues

A major concern following the Orbiter Deflection Maneuver (ODM) in July 1995 was that the helium pressurant checkvalve on the oxidizer side apparently was not closed[1]. ox pressure increases faster than fuel pressure with temperature. Any increase in propellant tanks temperature could cause the unchecked ox side pressure to crack open the. fuel checkvalve and result in helium convection of ox vapor to the fuel side. Electrical power margin, which is hardwire shunted to the propellant tank heaters, was maintained essentially constant to avoid convection, i.e.., the tank temperatures were held constant within 0.5°C. This was a major undertaking implemented by a combination of sending realtime commands to override the stored sequence commands and sequence changes. This operational requirement was enforced through the approach and Jupiter encounter and until shortly after the Perijove Raise (PJR) maneuver. Although potential for energetic reaction of propellants in the pressurization system was extremely low, all reasonable steps were taken to minimize the prospect of any propellant mingling. The leading candidate cause for the loss of the Mars Observer Spacecraft was liquid propellant mingling in a pressurization line.

The mission critical PJR maneuver was executed successfully on March 14, 1996. This was the final use of the 400N engine. The maneuver imparted 378 meters/sec to the spacecraft, and had an accelerometer controlled shutdown with a 0.2% underburn. With this maneuver, the Jupiter closest approach was raised to 11 Jupiter radii to,@ out of the intense Jupiter radiation. Several new requirements were part of this activity First, there was a concern about the filters in the propellant lines getting clogged by an overburden of particulates. If the filters restricted the flow to the engine, there could be clogging and potentially catastophic destruction of the engine which could risk the spacecraft. Because of this risk, new fault protection was added which monitored the propellant line pressures and would shut down the maneuver if required. The PJR maneuver could be completed later with the ION thrusters in such an event.

The other new requirement was to autonomously isolate the He pressure regulator immediately following the burn. The purpose of this was to eliminate the Ox checkvalve open concern by capturing a favorable oxidizer/fuel pressure gradient (0.5 bar higher on the fuel side) for mitigation against future oxidizer vapor transport. Following the PJR burn, an anomalous 0.7 bar low fuel pressure was observed so the Ox pressure was].? bar *above* the fuel ! A 3-4% low thrust was also observed consistent with the low fuel pressure. With this differential in pressure, it was highly likely that the Ox checkvalve was holding since normally the fuel checkvalve cracks at 0.5 bar-. Unfortunately, absolutely ruling out the possibility of vapor transport was still not possible. The analysis effort was then targeted to assess the worse. case consequences of vapor transport.

A thorough risk assessment by JPL/DARA/DASA established that there was essentially no risk of a harmful reaction in the event of vapor transfer from ox to fuel side particularly considering 1/3 the. tank volume of flesh helium was injected during PJR and diffusion rates are slow. Given these results, the power margin increase to 45 watts needed for the orbital tour was implemented with a 15 watt pad (total of 60 watts) on April 15, 1996. The tanks were allowed to thermally stabilize at higher differential pressures than originally planned for the rest of the mission.

The consequent increase in ox/fu pressure delta was close to expectation and no vapor transfer occurred. There is now no threat of vapor transfer during the tour because the pressure delta will remain well below that demonstrated. Evidence also is now overwhelming that the ox checkvalve is checking properly. Performing the orbital tour in blowdown mode (He supply isolated) is perfectly satisfactory and eliminates the pressurization system from any further operation considerations.

9 Loading of the Orbital Phase (2A) Flight Software (IFL)

The capabilities of the orbital Flight Software (FSW) are described in Reference 2. The design, test , and implementation of the command packages necessary to load the new Attitude and Articulation Control (AACS) and Command and Data Subsystems (CDS) and 8 of the 11 science instruments are described in this section.

The in-flight Load (IFL) had to fit in the schedule after the PJR in mid-March 1996 and before the first of the satellite encounters, Ganymede 1 (G1) on June 27th, a period of only 12 weeks, The goal was to complete the IFL early enough to return the Io Torus fields and particles science data recorded on December 7th, before the G1 sequence was uplinked to the Spacecraft (S/C). (See Figure 4.) On the basis of the Project experience with the IFL of the Phase 1 FSW, uplinked in 1995, 7 weeks were tentatively allocated for the Phase 2A IFL.

The plan, as shown in Figure 17, called for the loading of the various subsystems sequentially. Originally, the Project thought that the instruments could be loaded prior to the loading of either the AACS or the CDS and left in an idle mode until later. For some instruments, the Magnetometer (MAG), the Dust Detector (DDS), and the Near Infrared Mapping Spectrometer (NIMS), this was possible. Other instruments concluded that the load should be deferred until the CDS was loaded with the Phase 2A Flight Software. The Project also decided to checkout the CDS Science Virtual Machine (SVM) the collection of entirely new' functions that controlled the tape recorder, science data editing, compression, and management, and the downlink- the AACS ICT compression and each of the instruments as soon as possible after the IFL was complete.

The initial concept review of the IFL, by the Project was held on February 8th. The Project decided that it would not be necessary to test the Instrument load command packages on the Testbed. Testbed validation of the CDS and AACS IFL command packages would be required. For all commands associated with anomaly recovery, first time S/C activities, or activities that are very complicated, the Project has, since Launch, required that the commands to be sent to the S/C be pretested on the Testbed: the hardware and software equivalent

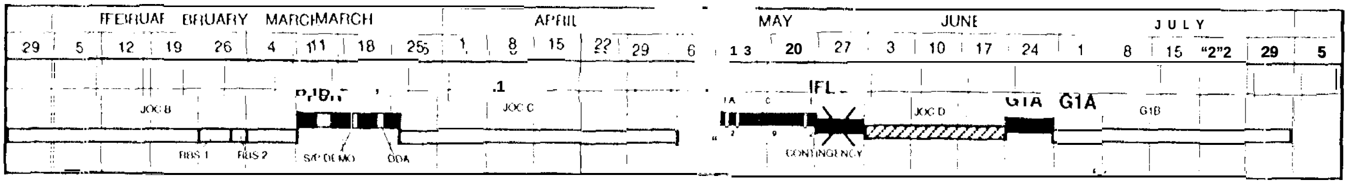

Figure 17. Overall Timeline

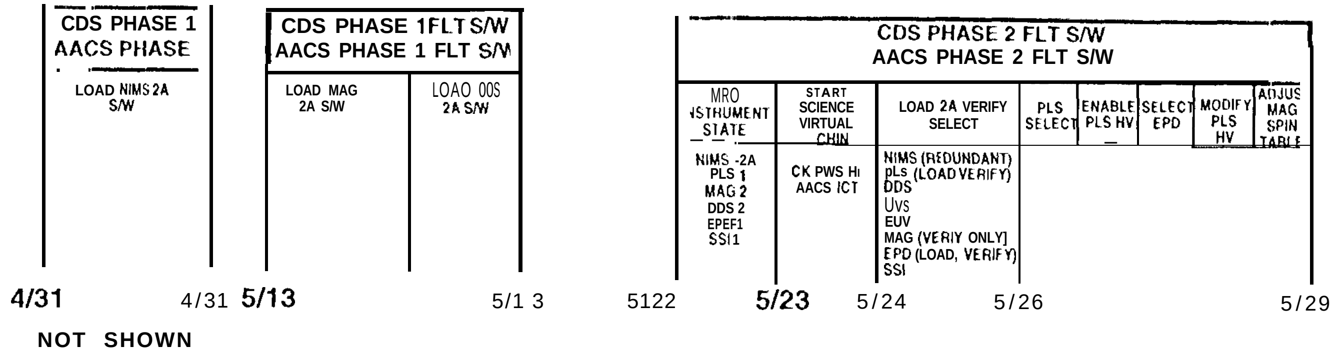

Figure 17a. Instrument Load Timeline

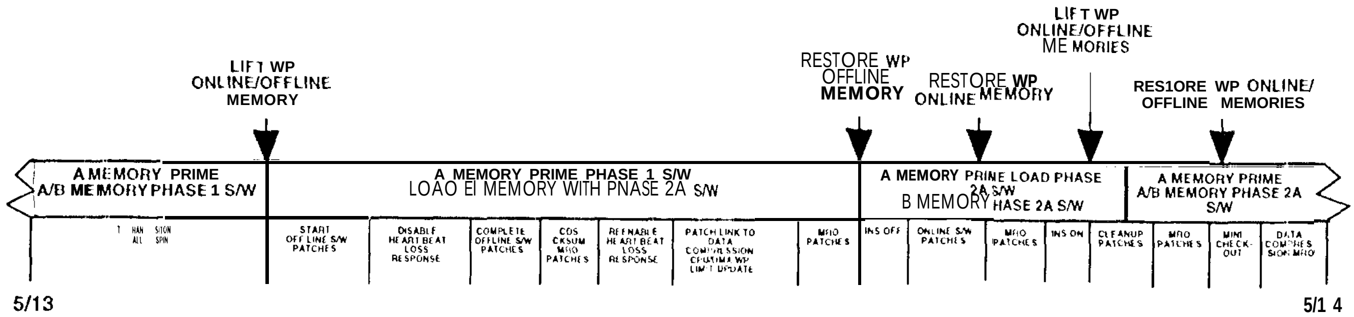

Figure 17b. AACS Load Timeline

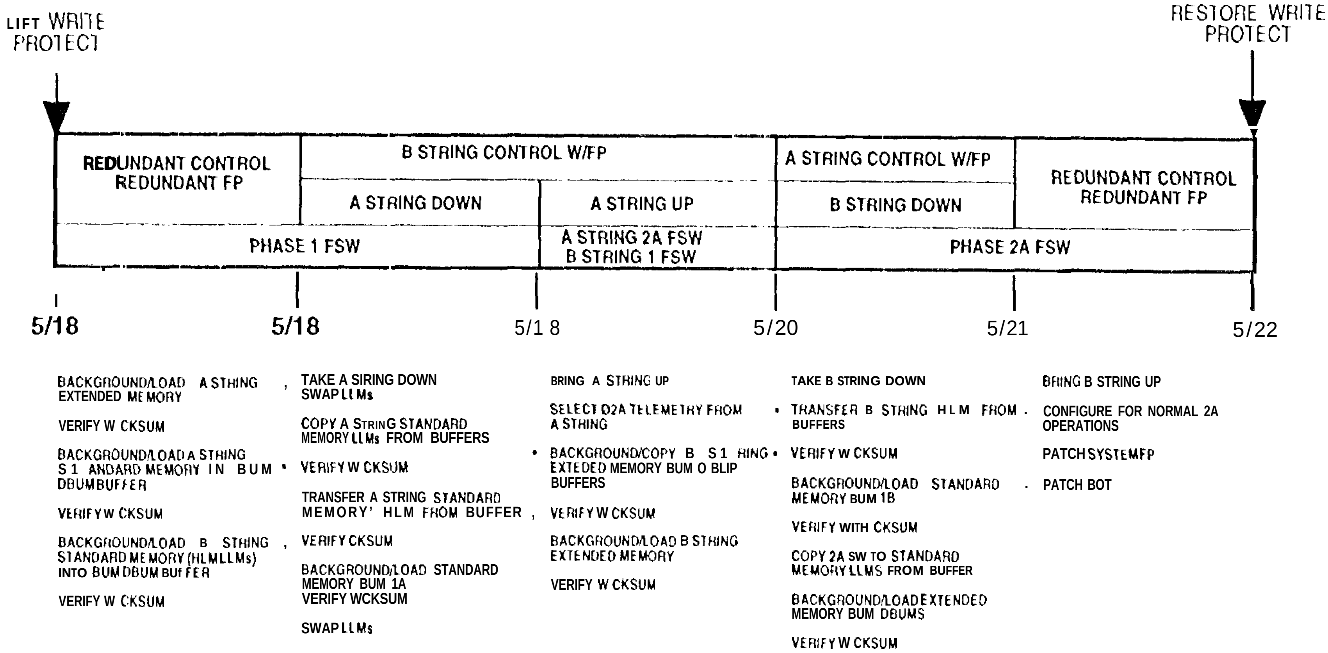

Figure 17c. CDS Load Timeline

of the Flight CDS, AACS and Tape Recorder (DMS). Earlier on, during the process of validating the Phase 2A FSW, the Engineering or Prototype Instruments were returned to JPL and were individually integrated into the Testbed. Prior to each of the instrument software tests, the commands that would later be used 10 transmit the Phase 2A software to each instrument were used to load the software in the ground based instruments. These tests had been repeated at least three times for cacb instrument. It was not considered essential that these commands be revalidated on the same test vehicle bc.fore transmission to the Flight Instruments.

After the concept review, informal testing of the CDS IFL commands was undertaken. These tests resulted in changes that were tested again until the commands would do the job. The Project then formal 1 y approved the command packages fot generation: translating the commands into a format that can be accepted by the tracking stations for transmission to the S/C. Following generation, the packages for the AACS and CDS were then retested on the Testbed. liven at this point, some problems were discovered and the Project bad to determine which of the requested changes were essential and what additional testing, if any, was required. From the time of the original Concept Review until the IFL started slightly more than three months had passed and 422 hours of test bad been accomplished. The Project was then confident that its intended long range brain sul-get y on the. spacecraft computers would be successful. As a by-product of the test program, a set of predicts which would allow the analysts to determine that it was safe to proceed to the next commanding step were available.

9.1 CDS Phase 2A Functionality

The Phase 2A CDS FSW was delivered on March 17th. At the time of the "final" delivery, there were several residual problems so accommodation for software rdcli\'cries or patches in the IFL command generation schedules and test plans was necessary. Most of this change traffic involved the new tape recorder fault protection. The final patches to the CDS software were delivered on April 17th, just in time for the find test of the CDS IFL and only 30 days before the uplink of the software began.

The scope of tile. changes to the CDS was massive. Fifty-eight plus percent or 224 kbytes of 384 kbytes of CDS memory were reloaded with code. 147 kbytes arc devoted to buffers necessary for internal data management and for sequence storage. Only 1 ?K bytes margin remain.

At Launch, the CDS was quad redundant with four identical copies of the CDS software stored in the memory. Phase I CDS used approximately half of the CDS memory to stoic Probe data so CDS operations became dual redundant al the last opportunity 10 ground command a memory swap which was days before the Probe Relay began. The Phase 2A was so large that even complete dual redundancy could not be maintained. However, health and safety functionality was redundantly maintained so if the spacecraft fault protection was required, it could be executed with separate bard ware executing duplicate copies of essential code. (This, in fact, occur red duc to a CDS fault on August 24, 1996 see Section 1.)

The new CDS Phase 2A included: packetized telemetry with advanced Reed-Solornon encoding, 8 downlink data rates (8- i 60bps), tape recorder record and automated, adaptive, table driven playback modes, science data selection, sampling, summation anti compression, and low rate real-ti[lw science downlink formats. As a special service to selected science instruments, automated loading of onboard stored mode dependent instrument software was provided. Real-tirrlc editing of optical navigation images was also provided using satellite limb finding and the exclusive downlink of star and satellite data only.

9.2 AACS Phase 2A Functionality

The scope of the.AA(X IFL was modest compared to the Phase 1 AACS IFL and much smaller [ban the CDS Phase 2A load. The AACS load \vas only 4600 bytes, most of which was loaded into the scratch pad area of the off-line or redundant memory. The necessary linkage allowing access to this patch by the AACS operating system had been loaded as a part of the AACS Phase 1 IFL.

New functionality included: Integer Cosine Transform (ICT) data compressor for the imaging camera and the Plasma Wave instrument data, the Gyro AACS input/Output (1/0) interaction was reduced 10 provide more timing margin when the ICT compression function was in use, automated Gyro drift determination for use (luring long duration turns at attitudes where star based attitude information would not be available, anti gyro heater fault protection changes.

Prior to the Phase 2A IFL, the AACS was fully redundant. The ICT compressor requires access 10 the off-line memory to operate thus this aspect of the new Phase 2A capabilities is not redundant. All AACS health and safety and all core engineering functionality remains redundant.

9.3 Instrument Phase 2A Functionality

Eight of the eleven instruments have computers that arc reprogrammable; for the. Phase 2A all eight delivered new sof'[ware. The deliveries occurred over several months with the final delivery on December 15, 1995. Four instruments had to redeliver the Phase 2A software to correct problems discovered in Instrument integration testing and /or system testing. in terms of the IFL, tire instrument software was available when needed.

Fundamentally, each of the instruments that \vas reprogrammed- SS1, NIMS, Ultraviolet Spectrometer (UVS), Dust Detector (DDS), Extreme Ultraviolet Spectrometer (EUV), Magnetometer (MAG), Energetic Particles Detector (11'1)), and Plasma (1'1 .S)- selectively included data summation, averaging, mode dependent data selection, and data formatting.

This was the first time since launch (bat all of the instruments capable of being reprogrammed were reloaded. In the past, individual instruments had been reprogrammed or patched to correct specific instrument software problems.

9.4 AACS IFL

AACS was commanded into the all-spin mode. Write protects were lilted and an abbreviated memory test of the appropriate portion of the off-line memory was completed.

The data compression portion of the Phase 2A software was uplinked and stored in the scratchpad portion of the off-line memory. Other patches were also loaded into the off-line memory. The newly loaded portion of the memory was checksummed and then a memory readout (MRO) was commanded. Verification of the memory load was accomplished using both the checksums and the MROs for redundancy because the relatively small size of the load. In order to speed the AACS IFL, the MRO of the data compression portion of this off-line memory patch was deferred until the very last step in the uplink process. The link between the data compression code now loaded in the off-line memory and the AACS operating system was patched. This patch allowed access to the new code. New write protect regions were uplinked and write protects were reestablished on the off-line memory. Patches to the on-line memory were then uplinked. These patches were verified with MROs. Write protects for the on-line memory were reestablished. Note that only the off-line memory contains the data compression code so this function is not redundant. If the on-line memory was somehow corrupted the AACS would automatically switch to the off-line memory and could provide total attitude control functionality except the data compression capability could not be supported in this configuration without reprogramming. After the on-line memory was loaded and validated, write protects were briefly lifted on both memories for some fault protection cleanup patches. Write protects were then reestablished. A mini checkout was commanded during which the AACS transitioned to cruise mode, the gyros turned on and off, the scan platform was slewed from one safe position to the other concluding with a transition to quasi-all-spin mode. This entire process is summarized schematically in Figure 17b.

Five separate command packages were generated and uplinked during the AACS IFL. Data was evaluated by the analysts in "real time." The analysts provided the three required "Go" recommendations on schedule. The AACS IFL took 24 hours and 40 minutes: two days had been set aside for this process.

9.5 CDS IFL

The CDS IFL is illustrated in Figure 17c. The entire CDS FSW was loaded from scratch. The core engineering functions of the CDS are located primarily in the high level module memory of the CDS and these functions were not changed significantly in Phase 2A, but they were relocated in the process of compiling the Phase 2A software.

Large portions of the CDS memory are not involved in the engineering operation of the S/C. In fact, once the Probe symbol data stored in the extended CDS memory had been played back (transmitted to the ground) this memory was unused. Further, during the CDS IFL, the S/C was not being controlled by a stored sequence thus CDS memory normally reserved for the purpose was not used. The CDS IFL design took advantage of the memory that could be loaded directly without interfering with the operation of the S/C. The availability of other unused memory also allowed the buffering or temporary staging of the Phase 2A software prior to its transfer to an area of memory that was in use controlling the S/C earlier on. This loading of FSW installments first into unused memory and later transferring to the ultimate memory locations speeded the IFL process and allowed for the greater use of onboard conditionals, i.e., checking progress by the flight computer without reliance upon analysts on the ground. During the Phase 1 IFL more than 27 "GO's" were required. Each involved analysts evaluating the state of the S/C and progress with the IFL. For the Phase 2A IFL, only 17 GO's were required even though Phase 2A CDS load required nearly 10 times the command volume of the Phase 1.

The IFL started with both CDS strings redundantly controlling the S/C operating with Phase 1 software. CDS memory write protects were lifted. The A string extended memory was loaded (uplinked) with the Phase 2A software. The A string normal memory was loaded into IFL staging buffers for subsequent transfer. The B string normal memory load was also uplinked into staging buffers. The A string was taken down. At that time, the B String hardware was controlling the S/C still using the Phase 1 software. The Phase 2A software was copied and transferred from the staging buffers or loaded via uplink commands into the A string normal memories. At each step in this process, successful loading was confirmed with onboard conditionals and selected checksums transmitted to the ground. The A string was brought up and as a partial Phase 2A software test, telemetry was returned to the ground using the A string and the newly loaded Phase 2A software while operational control was being exercised by the B string and the Phase 1 software. The B string extended memory was copied from staging buffers or loaded via uplink commands and verified by checksum. Control was transferred to the A string and the B string was taken down. The B string normal memory was copied and transferred from staging buffers and loaded via uplink commands. Again checksums were used to verify the correct loading. The B string was brought up, timing between the two strings reestablished and the engineering functionality was redundantly provided by the two strings. This is the standard configuration for planetary operations. This concluded the CDS IFL, however, the Science Virtual Machine was not started until two days later.

Forty-six separate command packages were generated and uplinked to the S/C during the CDS IFL. The shortest of the packages took 4 minutes, the longest took 3 hours 27 minutes to transmit. The average daily commanding duration was approximately ten hours. As was the case during the AACS IFL, analysts evaluated checksums and in some cases specific memory readouts in real time. The analysts provided 17 required "Go" recommendations. In three situations, commanding was delayed briefly to assure that predict miscompares were acceptable. There were minor delays but all 46 command packages were sent within the originally approved command windows; the longest delay was 6 .5 hours. The CDS IFL took 6.5 days : nine days had been allocated.

9.6 Instrument IFL

Compared the AACS/CDS IFL processes, the fundamental approach to the Instrument IFL was quite different. The software load was controlled by a comprehensive sequence which stepped through the load one instrument at a time as illustrated in Figure 17a. Following the load the instrument memory was checksummed, the instrument was turned on and its data selected for transmission to the ground, For most of' the instruments, definitive status assessment required the instrument to be operated and for science data to be evaluated along with the comparatively modest amount of instrument engineering data which is downlinked as part of the science data stream. The IFL approach assumed that any problems detected in the load of' a particular instrument, i.e., failed checksums, would result in the instrument turn-off by ground command. The subsequent loading of other instruments would continue under sequence control and after the sequence had been completed, trouble shooting and later the reload of the instrument would be considered. Fortunately, there were no problems with any instrument load.

Twenty-one command packages were generated and transmitted during the Instrument IFL. For loading the instrument software and a brief post-load instrument checkout, only five command packages were required. The balance, 16 packages, was used to evaluate the preload state of the instruments, manage the downlink during the post-load checkout and initialization of the instruments for the G1 encounter. The Instrument IFL including the G1 Initialization took 5 days.

9.7 Summary

The Phase 2A IFL was much more than the load of new flight software. It involved new ground based hardware and software cm-lo-cod, from the. tracking station to the computers at JPL, required to process and display the new data from the Spacecraft. It is of course true, that the new systems were all checked piece by piece and in integrated tests prior to the IFL. However, never before in the history of planetary exploration were such comprehensive changes attempted with a flying Spacecraft! BUT, IT WORKED! It worked without a significant problem. This is a tribute to people on the Galileo team at JPL, the tracking stations at Madrid, Goldstone, and Canberra and at Science Principal Investigator locations.

The IFL was accomplished in fourteen days; 21 days had been allocated. The process was delayed a total of five times, but only twice because of ground system problems. There was a power outage in the control center at JPL and a command system software problem associated with the delay times between commands when breaking command packages into smaller sets of commands. The command system problem was corrected before transmission. The level of command activity was also unprecedented! Only one delay, 4 minutes, was attributed to the tracking stations during the IFL. Total radiation time during the IFL exceeded 81 hours. There were two days in which commanding exceeded 14 hours. The average daily radiation time during the two week period was 10 hours. For the Phase 1 IFL in 1995, daily commanding averaged 5 hours and the Project considered that a record!

10. Real-time Operations Specialties

10.1 Emergency Project Operations Center

Trajectory errors, if uncorrected, could preclude a successful orbit insertion prerequisite to the planned Jupiter orbital tour. Since maneuver sequences are developed using the latest received tracking data and are built upon the previous maneuver execution and orbit determination accuracy, they could not be generated apriori and stored for later use. Consequently, the need was established to generate and transmit these critical sequences at the planned times and to be able to transmit contingency commands. Realizing this, the Project concluded that an alternative Mission Operations Center capability should be developed that would permit generation of these maneuvers, sequences, and commands should the JPL operations facilities become unusable. It was assumed that a major earthquake centered in the vicinity of JPL would render the spaceflight operations buildings inaccessible to the flight operations personnel making it impossible to develop and transmit the sequences or commands. The mission would be at great risk. A team was formed in April 1995 and chartered to identify, develop, and integrate all necessary operations at a remote site which could be used by selected members of the flight team to ensure successful development, transmission, and execution of any critical sequences or commands. As a first step in establishing an Emergency Project operations Center (EPOC), a detailed review of the activities specified by the Mission Plan was performed which confirmed (beer-iticality of the maneuvers. Radiometric tracking of the spacecraft, telemetry monitoring, commanding, sequence generation, communications and data flow to and from the Deep Space Stations were identified as the operations functions needed.

Upon review of the statistics report of the Northridge earthquake of 1994 issued by the U.S. Department of the Interior, U.S. Geological survey, it was determined that a site outside a 25 mile radius of JPL would most likely remain available for use.

The 70 meter Deep Space Station at Goldstone, California, 110 miles away from the JPL was selected and the team began the Emergency Project operations Center design. This site had several distinct advantages besides its remote location. Communications and data flow existed and electric power, air conditioning, and an unused operations area were already in place. The bulk of the EPOC implementation lay in computer procurement, software installation, and testing.

Processing of the telemetry and command data was provided through integration of a complete. set of Advanced Multi-Mission Operations System (AMMOS) software that had been independently developed by the JPL Multi-Mission Ground Data System. This software was transported to Goldstone, integrated into the hardware provided by the Project, and tested thoroughly.

On November 2, seven months after the Project go-ahead, a command was sent to and received by the Galileo spacecraft and telemetry data was processed thereby demonstrating the operational readiness of the EPOC. The EPOC stood ready if needed and happily was not, but it is serving as a model for future flight projects.

10.2 Relay/JOI

The Deep Space Net (DSN) Block V Receiver (BVR) and Ultracone feed system were two recently delivered pieces of ground support hardware. The BVR was designed to replace the technically obsolete Block III and Block IV receivers. In addition to providing radiometric data and an increase in telemetry data quality, the BVR had the capability of tracking a residual or a suppressed carrier. Tracking a suppressed carrier was of great import to the Galileo Project. Because of the High Gain Antenna (HGA) problem, the Project had to track the spacecraft using the much weaker signal transmitted by the Low Gain Antenna (LGA). By suppressing the carrier, more power could be put into the data sidebands thereby increasing the data Signal to Noise Ratio (SNR). To capture this data, however, required a ground receiver that could lock onto the sidebands without a carrier being present. The BVR performed this function. Performance improvement of approximately +0.5db was achieved. Another SNR improvement was achieved through the use of an ultralow noise S-band (2.3 GHz) feed system installed in the 70m antenna at Camberra, Australia. This feed system commonly called the Ultracone has better performance characteristics than the S-Band Polarization Device (SPD) system that was normally used. The Ultracone allows the receipt of higher data rate transmissions from the Galileo LGA. The performance improvements were achieved through lowering the System to Noise Temperature (SNT) from 15.6° Kelvin to 11.8° Kelvin at zenith. This provided an increase in received signal of over 1db and a projected increase in data return over the mission of approximately 10%. Both the BVR and Ultracone supported the Relay/IOI operations flawlessly. Doppler data was provided throughout the Io and Jupiter closest points of approach. Telemetry data was missing but the processors remained in lock. Critical ground commanding was performed without fault even though the Goldstone 375KW Transmitter experienced coolant leaks which, if system interlocks had not been manually bypassed, would have automatically turned the transmitter off. On December 7, in real-time, engineers confirmed spacecraft lock on the Probe data and the start of the 400N engine burn was seen in the doppler data and confirmed in the telemetry signal. However, immediately at ground receipt of the end of the burn, one of the two Receiver Channel Processors (RCP) of BVR dropped lock on the telemetry signal. The other RCP maintained lock for an additional 1 hour 30 minutes before installing new predicts caused a telemetry outage. This outage lasted for 12 minutes, but the main orbit insertion events had already been confirmed.

10.3 Perijove Raise Maneuver

On March 14, the Perijove Raise Maneuver (PJR) was performed at an attitude of 46.5° off-Earthline resulting in a 4db weaker signal for ground operations than was received during JOI. The PJR sequence started in the suppressed carrier mode. Five minutes prior to burn, residual carrier mode was commanded by the on-board sequence to increase the prospects that the BVR ground receivers would maintain lock on the spacecraft signal to provide doppler data and possibly telemetry during and after the burn. During the burn, doppler data remained in lock and was provided. However, telemetry data was lost due to the low received signal levels. At burn stop, all ground received signals were lost. Automatic attempts to reacquire resulted in a false lock which does not permit actual data processing. After a period of time, ground operations recognized this condition and manually reloaded the BVR receivers. Telemetry was not reacquired for an additional 30 minutes. The experimental Full Spectrum Recorder (FSR) supporting the PJR on a best efforts basis did maintain lock and showed a frequency offset of 4.8 Hertz from the predicted frequency. Quickly applying his offset into the BVR resulted in a reacquisition of doppler data that confirmed that the PJR maneuver had executed as planned and gave early indications that the spacecraft was healthy and functioning properly.

10.4 Ganymede 1 Encounter

To track Galileo's low signal levels, the DSN developed the Deep Space Communications Complex Galileo Telemetry subsystem (DGT). The DGT consists of two channel operations; one channel for Block V Receiver support and the other based upon a Full Spectrum Recorder (FSR). Telemetry processing is done independently by each channel. This approach reduces the risk of loss of data due to equipment failure. The BVR channel for Galileo Orbital Phase (packetized) telemetry was not yet available for this first encounter. The FSR channel commonly called the "single string" was available and committed as the prime data acquisition source. It was for this equipment that the signal level analysis was performed so that optimum bandwidth settings could be predicted and used to lock and process telemetry. Concern over the ability of the ground hardware to maintain lock on the doppler and telemetry during the closest approach was heightened when the expected signal analysis was compared to the operational profile. It was decided to request the Array DGT, a system being developed that combines telemetry data from multiple tracking antennas through a Full Spectrum Combiner (FSC) and slated to replace the Single String DGT, support the encounter on a "best efforts" basis. Use of the system would give the Project a backup acquisition and tracking source in the event failures occurred in the Single String DGT. This decision proved to be sound as the Single String DGT system never obtained levels on the signal during the encounter. This was traced to predict problem. The Array DGT, however, did maintain signal acquisition and tracking through the closest approach period providing the Project with real-time visibility that the encounter was successful.

11.1 Ganymede-1 Encounter Sequence/Performance

The first encounter of the tour was with Ganymede (G1) on June 27, 1996, at an altitude of 835 km and a latitude at closest approach of 30.4 deg. The spacecraft sequence that accomplished the data acquisition ran from June 23, 1600 GMT, to June 30, 0430 GMT. During this period, data were acquired by two methods- real-time and recorded. The RTS (Real-Time Science) data came from primarily the Fields and Particles instruments, with some additional participation by NIMS and UVS. This data is processed as acquired by the CDS and sent directly to Earth with no on-board storage other than for short periods in the multi-use buffer. The recorded data came from all the instruments except EPD, and was stored on the DMS for return to Earth during the approximately two month cruise period before the second encounter in the tour. Data recording was limited to tracks 2, 3, and 4 on the DMS, because track 1 had been used to store 10 torus data that had been acquired during the initial pass by Jupiter on December 7. The Probe data had also been stored on track 1, but was completely returned prior to the first satellite encounter.

The nominal plan was to return the torus data in the JOCD sequence (the last sequence before Ganymede), but since that was the first sequence to operate with the new phase 2 system, there was considerable question about when the sequence would start and how well it would perform at the time the G1 recording sequence was being designed. Hence, the decision was made not to record on track 1 to insure that there was no risk of overwriting any of the torus data before it was successfully returned. In fact, the JOCD sequence started at the planned time and worked very well, but there were still numerous pieces of the torus data that were not recovered during that period that were subsequently recovered during the G1 playback period.

Figure 18 shows a plot of the spacecraft path. The locations of the various instrument observations are indicated, from which one can determine a quite accurate sense of the geometry involved, including primarily ranges and lighting angles. Figure 19 shows a linear timeline of the same observations. The UVS/EUV observations are early, well before perijove, because of geometrical considerations. In fact, the bulk of their torus observations were accomplished in the JOCD sequence before the G1 encounter sequence started, and were not recorded but rather came down as real-time data. The SSI observations give the appearance of being the least intensive, but in fact were far from that. This appearance is the result of the fact that the other remote sensing instruments tend to operate in scanning modes, as opposed to the relatively instantaneous shuttering of the camera. A total of 129 images were taken and recorded, of which at least portions of 127 were later returned. The activity line at the bottom of Figure 19 indicates the period where the fields and particles instruments were returning continuous data in support of the magnetospheric survey.

Figure 20 shows a map of the locations of the recorded data on the DMS. Recording started at the beginning of track two (on the right), progressed from right to left, changed to track 3, recording from left to right, then completed on track 4 from right to left. In the course of recording on track 3, it was determined from the real-time engineering telemetry that the DMS was using more tape than had been expected, and to insure that the recording did not extend into the end-of-track marker, real-time commands were send to truncate the NIMS Jupiter Observation near the end of the track by about 150 tics of tape. This represented a small percentage reduction of a fairly long observation, and was of fairly minimal impact. Analysis after recording was complete was ambiguous as to whether this action prevented writing into the track marker, but in any event, it would have been very close. Tape usage model parameters have been updated based on this experience to avoid similar risks in future sequences.

The overall G1 encounter data acquisition process worked very well. All of the spacecraft engineering systems, including the DMS, performed without flaw. Three science instruments, NIMS, PPR, and EPD, experienced problems leading to restricted data acquisition.

11.2 Ganymede-1 Playback Operations and Performance

The planned period of recorded data return for the G1 encounter data ran from July 1, 0424 GMT to September 1, 0000 GMT. Overall, the activity was highly successful, with most of the useful data being returned. The initial plan did not expect to return all of the recorded data due to the limitation on downlink capability using the low-gain antenna. A major uncertainty in how much data would actually be returned was the performance of the onboard data compressors. In fact, their performance ranged from about as expected, in the case of Rice compression on the PLS data, to considerably better than expected for the ICT use on some of the SSI data. This allowed the return of more data than the original predictions indicated, especially since the initial plan assumed 1:1 compression for 4 of the 6 data types that used Rice compression, as a conservative assumption for the first use of this capability. The lack of any EPD data, and the fact that some of the PPR and NIMS data were of minimal value because of their instrument anomalies also led to more return capability for other instruments, most notably SSI.

The playback started part way through track 3 with the return of relatively high resolution (~75m) SSI images in the regions of Uruk Sulkis and Galileo Regio on Ganymede. This was done to support an early press conference after the Ganymede encounter since these were the first images returned by Galileo from Jupiter, and they had been a long time in coming relative to initial expectations because of the DMS anomaly. When this initial return was complete, the tape was positioned to track 1 to return the remainder of the Io torus data recorded in December 1995, which had not been returned in JOCD for various reasons, mostly station outages and data frames lost due to issues related to the first use of the phase 2 ground system. This amounted to about 10% of the total torus data set. The plan at this point was to proceed straight through the tape in time order, deselecting the images that had been returned earlier. However, around this time, additional testing of the playback manager code in the testbed had uncovered a serious problem that was likely to occur when processing NIMS data that could halt playback. The action taken was to proceed across the tape in time order as planned, but to deselect all the NIMS data up until such time that a flight software fix could be implemented. From that point onward, NIMS data would be included in the return, and another pass through the tape up to the point of where the NIMS selection began would be done to recover the NIMS data skipped to that point. The fix turned out to be a difficult problem, and it was completed at just about the time the other planned non-NIMS data return was completed, i.e., near the end of track 4. On August 1, the fix was onboard and the pass to return primarily NIMS data was begun. By this time, the benefits of the Rice and ICT compression performance had been realized, and other data that had been deselected the previous time through, primarily

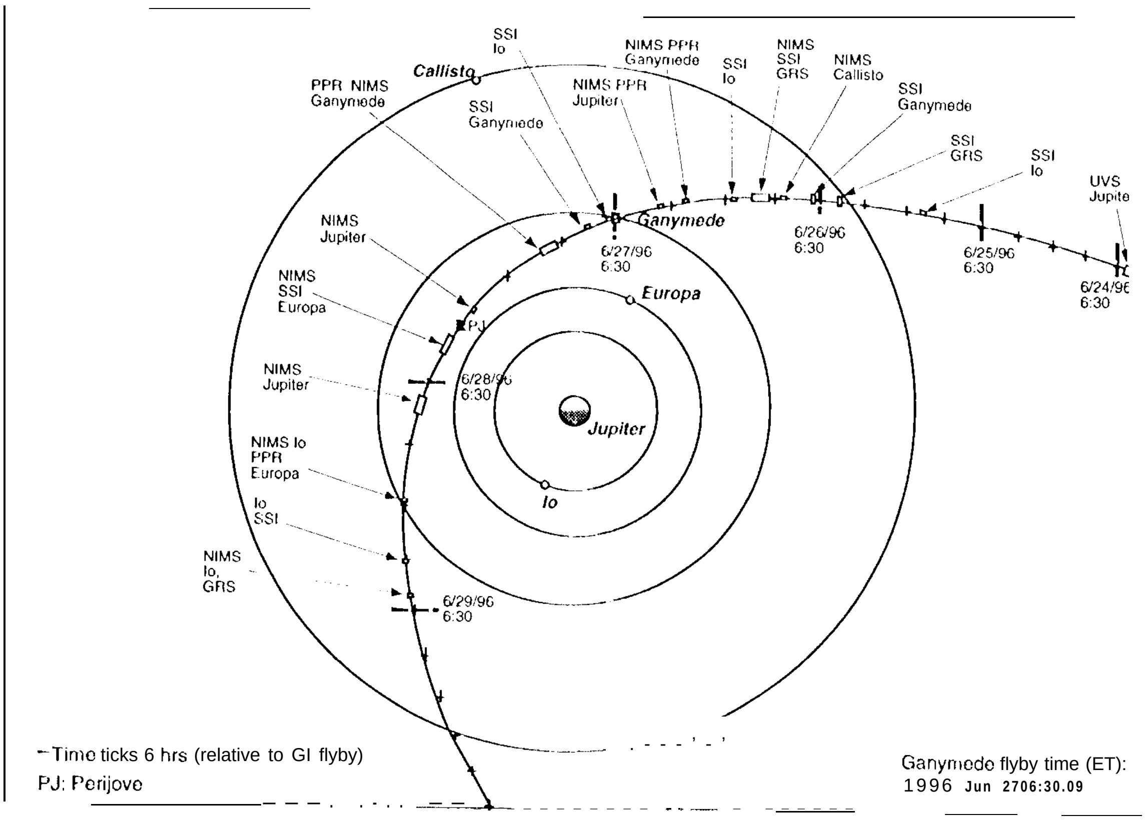

Figure 18. Jupiter: North Trajectory Pole View (G1 +/- 3 days High Level Record Map

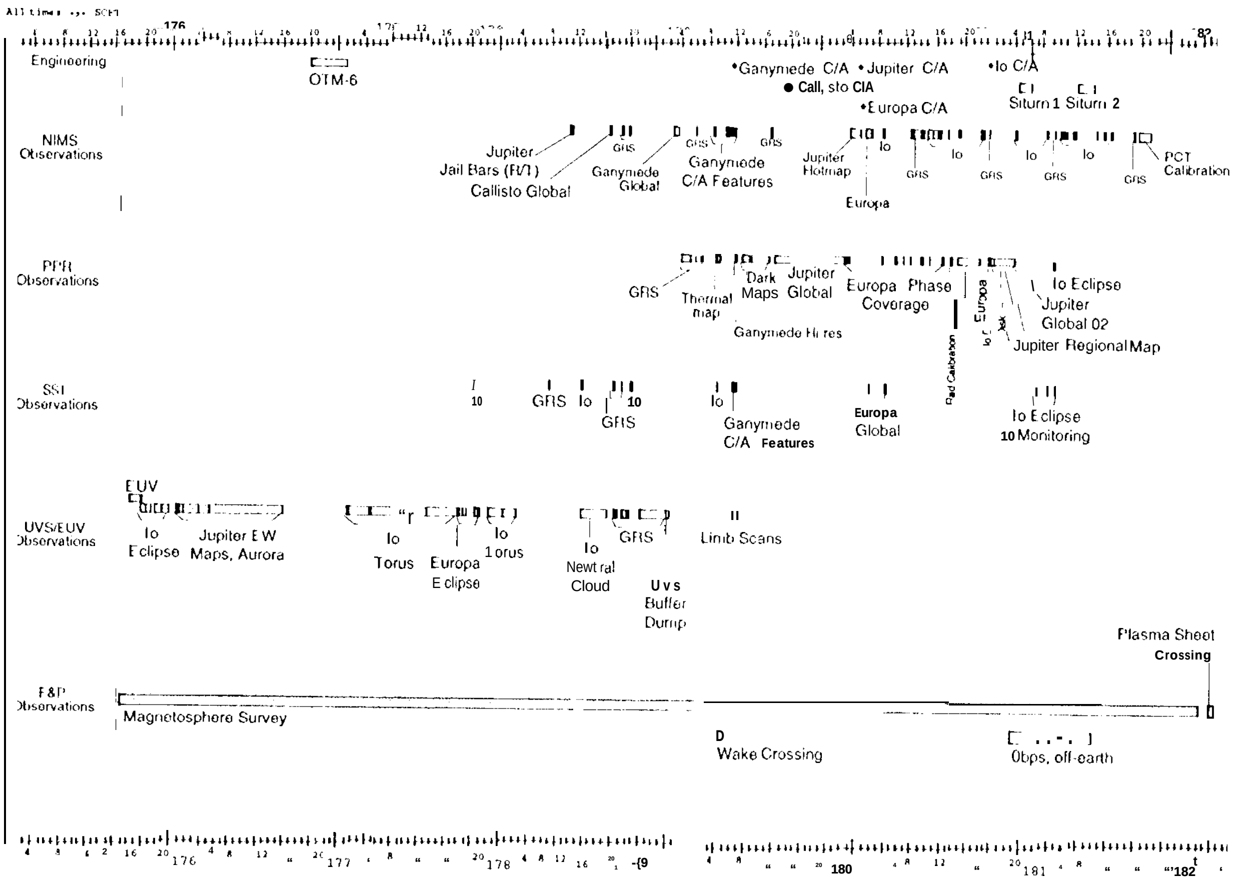

Figure 19. G1 Encounter: Science Activities

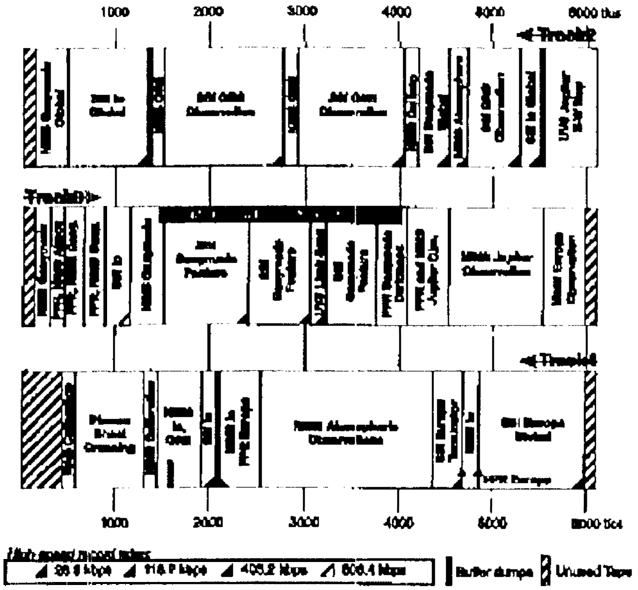

Figure 20. G1 High-Level Tape Map

SS1, was also selected for return. However, at about this point, another playback manager problem was found that could cause the process to hang up when processing medium rate NIMS data, the first NIMS observation data set on the tape. This data set was deselected, and the process began by returning low and imbedded high rate data. From here, the process worked well until near the end of track 3, when the process found the point at which the NIMS anomaly occurred (see introduction), considerably earlier than had been expected based on the very limited real-time data that was available earlier. This caused the Rice compression to go from about 2:1 to 1:1, i.e., no compression due to the erratic nature of the data. The volume of NIMS data remaining and the lack of compression meant that the process would not reach the end of the tape by the end of the cruise period if no intervening actions were taken. Also, since the remaining NIMS data was of questionable scientific value, it was appropriate to deselect it in favor of other previously deselected data. Commands were sent from the ground to pause the playback, most of the remaining NIMS observations were deselected, more SS1 data were selected, and the process was resumed.

There was reluctance to starting yet another pass through the tape because of the additional tape recorder usage. However, if playback were to end when the end of track 4 was next reached, there would have been several days of time remaining with no playback occurring, because of all the corrupted NIMS data that had been deselected, and valuable data still remained on tracks 1 and 2. Some PWS data still remained on track 1 due to a software feature that was previously not well understood, the original medium rate NIMS observation was a very high priority data set, and several SS1 images on track 2 were prioritized for replay at lower compression. Ultimately, it was decided to loop around to track 1 and part way through track 2 to acquire these data sets. On August 24, the spacecraft went into safing due to a timing overrun condition in the CDS, which terminated the sequence, ending any further data return from the G1 sequence. Prior to this event, the PWS data on track 1 was recovered, but the additional SS1 and NIMS data were not. Also lost were RTS data, including the UVS 10 torus observations scheduled for the last few days of the G1 cruise sequence. By September 1, the spacecraft had been returned to normal operation, and the G2 encounter sequence began right on schedule.

11.3 Ganymede-2 Encounter Sequence/Performance

The spacecraft orbit after JOI was inclined to the equatorial plane of Jupiter, and the orbital plane of the Galilean satellites, by about 5.4°, because of the non-zero approach declination of the interplanetary approach trajectory to Jupiter. Since having the spacecraft orbit lie in the orbital plane of the satellites is a necessary condition to have encounters with more than one of the satellites, it was necessary that all encounters be with the same satellite until such a zero inclination condition could be achieved. Ganymede was chosen to be this satellite, because its mass and orbital location were favorable for changing both period and orbital inclination. The first encounter gravity assist at 30.4" latitude primarily served to reduce the initial period from 210 days 72 days, but also contributed slightly to inclination reduction. The second encounter at 80° latitude was primarily to make the Galileo orbit co-planar with the satellites' orbits, thus enabling subsequent encounters with Europa and Callisto. This second encounter occurred on September 6 at an altitude of 260 km.

Although the latitudes at closest approach for these two Ganymede encounters were driven by the above orbital mechanics considerations, they serendipitously provided an ideal arrangement for one of the high priority radio science observations. The first relatively equatorial pass and the second near polar pass will allow a measurement of Ganymede's gravity field and an indication of the internal structure of the body. The Doppler data were successfully obtained for both encounters and are being analyzed.

At 260 km altitude, this G2 encounter was the closest approach of all of the 10 encounters planned for the tour. Remote sensing observations were made of all four of the Galilean satellites on this pass through perijove. Callisto and 10 were seen at ranges a little over 400,000" km, and Europa at a more distant 671,000 km. The six fields and particles instruments maintained continuous downlink throughout in support of the magnetospheric survey, as well as recordings near Ganymede closest approach and at the plasma sheet crossing about four days after the encounter. With the exception of the PPR not being turned on to collect science data due to its earlier filter wheel anomaly, the encounter period data acquisition and real-time return was a complete success, accomplishing all objectives with only one relatively minor problem. The NIMS instrument again experienced the same kind of problem as in the G1 encounter. However, because of a previously planned reload of the instrument memory from the CDS during the encounter period, the instrument was nonfunctional for only about a five hour period, resulting in minimal loss of observations.

Figure 21 shows the path of Galileo spacecraft for this Ganymede encounter, and a description of where the main

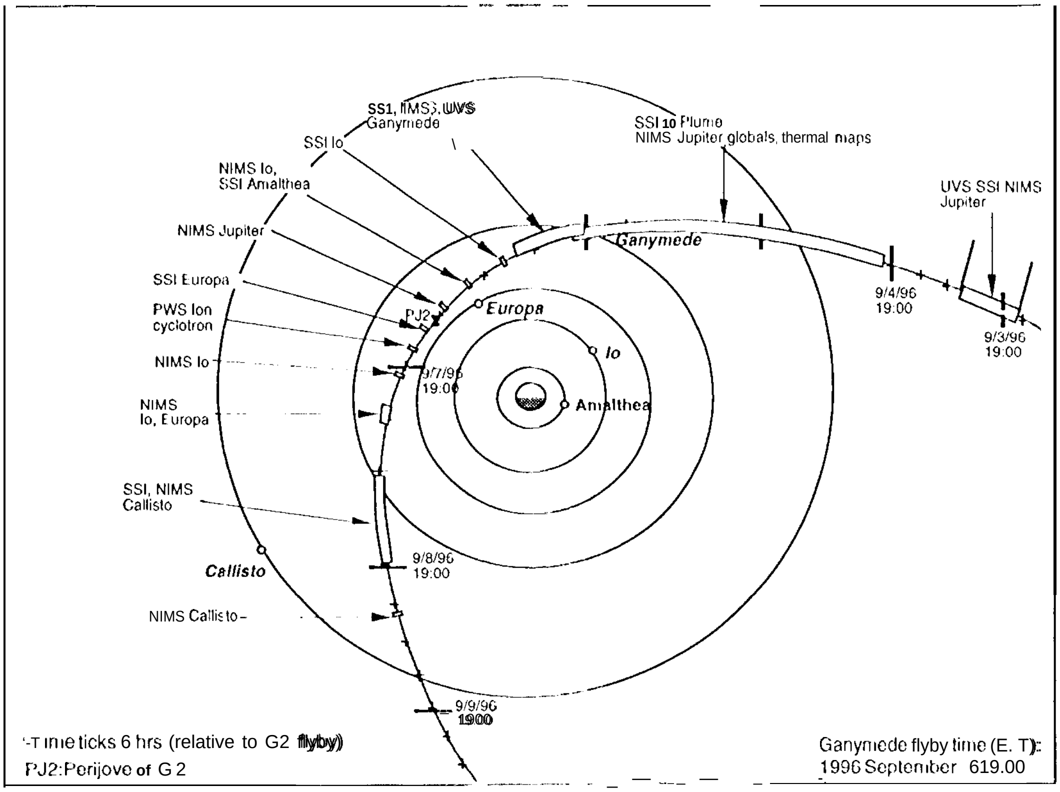

Figure 21. Jupiter: North Trajectory Pole View (G2 +/-.3 days) High Level Record Map

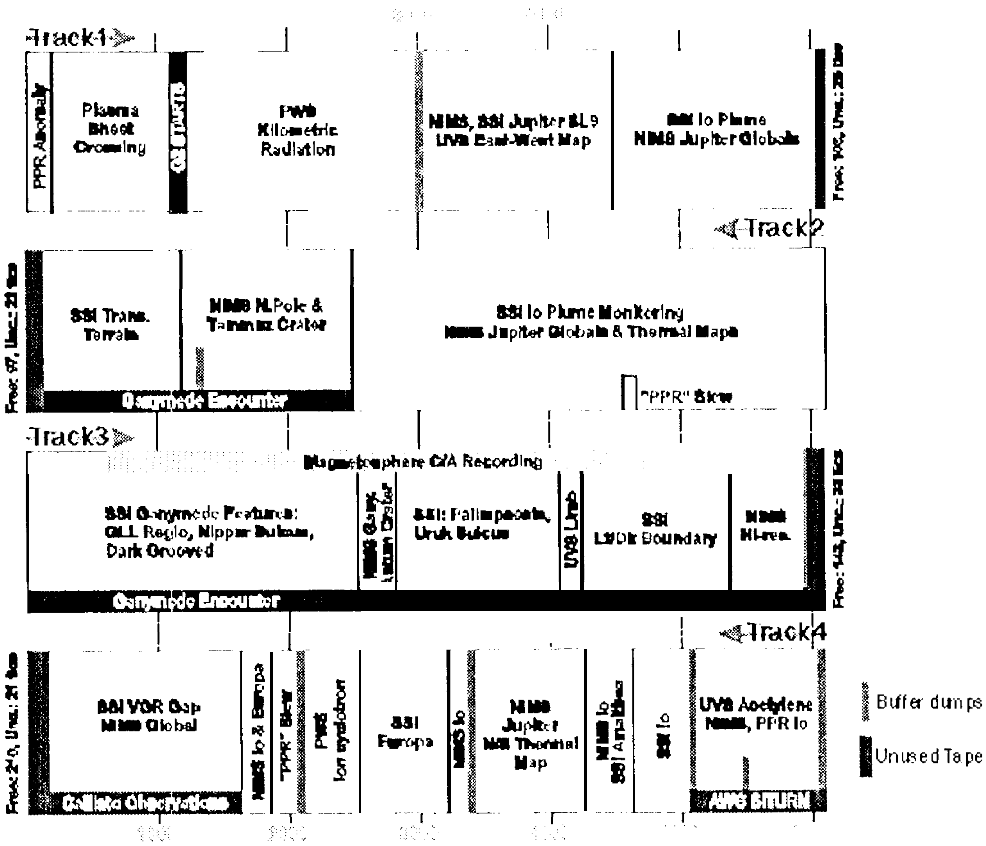

Figure 22. G2 High-Level Tape Map

observations were taken. Figure 22 shows the map of the data as placed on the DMS.

12. Acknowledgment

Project Galileo represents the work 01 thousands of people. They all deserve acknowledgment for the many accomplishments of Galileo 10 date and for the tremendous promise it holds at Jupiter.

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